The Costs of Adaptation to Climate Change in Canada: A Stratified Estimate by Sectors and Regions

CCAF Grant # A 209

By

Mohammed H.I. Dore
Brock University

And

Ian Burton,
A.I.R.G., Environment Canada

First Deliverable: A Review of the Literature on the Costs of Adaptation to Climate Change

Final Version date: November 15, 2000

A Review of the Literature on the Costs of Adaptation to Climate Change

Table of Contents

Preface

This review was written under the CCAF Grant No. A 209. The guiding questions in writing the review were: (1) What is known about the theory and estimation of the costs of adaptation to climate change? (2) In view of what is known, where do we go from there? As often happens, it took us much longer to attempt to answer these two questions than we anticipated. Both Burton and Dore were joint authors of an earlier review of the literature (Burton and Dore, 2000), which was designed largely to update Chapter One of the Canada Country Study (1998). In the present review, the authors have tried to be more reflective and were very mindful of how one might actually go about estimating the costs of adaptation to climate change not at the aggregate GDP level but at sectoral and individual unit level, such a bridge, or a road. For this reason we have attempted to provide a review of a fairly technical theory of adaptation costs as well as sectoral estimates of adaptation costs, in so far as these have been published in the peer-reviewed literature.

In view of our earlier review, we have tried to complement this work by avoiding duplication but at the same time making the present review self-contained and complete. We have kept in mind three kinds of readers who might be interested in the review: the specialized climate change scientists, readers interested in policy formation, and the top level decision makers. We expect that the climate change scientist will want to plough through the entire report. Those interested only in policy formation may easily skip the mathematical sections of 2.2 to 2.5 and go to section 2.6, which has a comprehensive summary of the technical material, without any loss of continuity. Finally, senior decision-makers with limited time may wish to read the Executive Summary, and perhaps dip into the comprehensive section summaries.

We were fortunate in receiving assistance from a large number of people in writing this review of the literature. At Brock University, we would like to thank Kathleen Jaques Bennett, Harvey Stevens, Mireille Trent, and Klemen Zumer who continue to work or at one time worked at the Climate Change Lab at Brock University. In addition, we received generous help from two librarians at Brock University: Margaret Dore and Moira Russell. At Environment Canada, we would like to thank Indra Fung-Fook, Ash Kumar, and Roberta McCarthy. However, any remaining deficiencies are those of the two authors alone.

Executive Summary

This report is a critical literature review in order to determine what is known about the theory and application of the costs of adaptation to climate change, with a view to specifying a complete methodology for estimating the micro level costs of adaptation to climate change in Canada. The report is in three parts: the first part is an introduction. The second is a detailed examination of the costing methodology. The third is a review of sectoral costs of adaptation. The final part is a synthesis of what is known and what needs to be done for Canada. What follows is an integrated summary of the three parts.

1. In climate change, what are costs and what are benefits depends upon the criterion of valuation that is used. There appear to be two schools of thought that may be called the "standard environmental economics" and "ecological economics." However, in both approaches the fundamental basis of valuation is the same - the technique of valuation is based on some measure of consumer satisfaction, either consumer's willingness to pay (WTP), or consumer surplus (CS), or consumer's willingness to accept (WTA).
2. Recent developments in economic theory show that the divergence between WTP and WTA could be in the interval $(0,\infty)$. The three measures of value coincide only under specific assumptions about preferences. In general, we know that WTP < CS < WTA. If quantity changes are considered, then the conclusion is further strengthened with WTP = 0 and WTA = ∞. This creates problems for valuation based on the utility of consumption.
3. This consumptionist approach requires the assumption of a representative consumer, who is assumed to be maximizing his/her utility. Assuming declining marginal utility, the utility maximizing model yields a demand curve. A measure of this consumer's well-being (or "advantage") is the integral under the demand curve. In order to get an invariant measure of value, it is necessary to assume that this representative consumer has "homothetic preferences". This is incidentally patently false because the best-established law in economics (called Engel's Law) shows that preferences are *not* homothetic. Specifically, Engel's Law states that total expenditures on food, as a share of income, falls as income rises. Furthermore, in order to obtain a numerical estimate of WTP, CS or WTA, one needs to use specific functional forms of the demand curve. Thus, any numerical estimate of value will depend on the specific functional form used to represent the demand curve. Experimenting with a variety of functional forms does not lead to a convergent optimal policy, as the basic economic model is structurally unstable.
4. According to standard environmental economics, any adaptation to climate change can be justified only in terms of increases in some measure of the consumer's "utility", such as consumer surplus (CS). Any adaptation to climate change will have a cost. Therefore, at the margin, the optimal amount spent on adapting to climate change will be determined by equating the marginal increase in CS to the marginal costs to the representative consumer. Hence, the adaptation can never be complete, unless it can be achieved at zero cost, which is extremely unlikely. At the margin, the amount spent on adaptation must equal marginal benefits with marginal costs.

5. The influential study by Nordhaus treats climate change as marginal only because the large non-marginal change will be spread over a period of 100 to 300 years. When the annual marginal costs and benefits (to the representative US consumer) are spread over hundreds of years *and* discounted, the discounted net stream benefit of reducing GHG reduction appears small. It is therefore not surprising that he concludes that the benefits are also so small that the optimal policy is to reduce GHGs by 13.4 percent by 2075.
6. We are largely in agreement with UNEP's critique of the methodology of estimating costs of adaptation; however we argue that climate change cannot be viewed as a "marginal" project, such as a local oil spill. (Climate change is a global negative "public good.")
7. Therefore the optimal quantity of adaptation cannot be determined by the rule that the incremental benefits must equal incremental costs because of the fact that the benefits of adaptation cannot be assumed to increase at a decreasing rate; i.e. the benefits function cannot be assumed to be "concave."
8. Benefits are usually defined to be the damage costs avoided through successful adaptation. But if the benefits are disaggregated to be the "chronic" costs of the steady decline of infrastructure, and the "acute" costs damages due to extreme weather events (such as floods, or the ice storms), then the benefits function will not be concave. In fact the function is likely to be nonlinear, and the choice of adaptive policies is likely to be discrete and "lumpy" at the micro level.
9. For the reasons given above, we conclude that the consumption-based valuation approach is not the best approach. Instead we propose to interpret the costs of adaptation as *investments,* and consequently propose an approach that is akin to portfolio choice theory in the theory of finance, including *option values,* where the objective is capital preservation. This approach views the biosphere as a portfolio of natural assets that yield perpetual dividends in the form of ecological services. Therefore, in so far that adaptation applies to *natural capital,* adaptations to climate change should be viewed as a portfolio management action designed to preserve the capital assets and their perpetual dividends, where climate change is a change in the distribution of these dividends which can threaten the integrity of the portfolio of assets. For human-made capital, the adaptation expenditure is also an investment (replacement or retro-fitting), provided that the piece of capital is not obsolete.
10. It follows that the key guiding principle should be the preservation of capital, both natural and human-made. The preservation of capital cannot be guaranteed by the rule that expenditures on adaptation should equate marginal costs with marginal benefits. The preservation of capital should be guided by the ultimate objective of preserving the way of life of Canadians and ensuring continued improvements in their standard of living.
11. UNEP (1998) correctly distinguishes *economic opportunity costs*, which, if taken seriously, indicates what is at stake here. The classical concept of economic opportunity costs defines what society would *lose*, if the natural and human-made assets were damaged or destroyed. The quantity of adaptation cannot be determined by smooth, linearly additive marginal cost and marginal benefit curves. In the real world, adaptation costs would be “lumpy” and therefore nonlinear. The literature on option values shows that, in some cases, adaptation may require over-dimensioning in

order to take into account nonlinearities.

12. The preservation of capital is an "investment approach", whereas the MB = MC rule is a based on a "consumption-based approach," and in the latter, the declining marginal benefits are assumed to be similar to consuming any other goods. For consumer goods, it is reasonable to assume that the marginal utility of consuming *more* of a particular consumer good declines. When expenditure on adaptation is in the form of investment, it cannot be assumed that the marginal "utility" of natural and human-made capital will be declining with increased adaptation. It must be remembered that the benefits are the costs avoided (see 8 above).
13. As indicated in 8 above, *part* of the benefits of adaptation would be an improved ability to deal with extreme weather events, such as the Red River and Saguenay floods, the Calgary Hail storm (in 1991), and the Ice Storm of 1998. Adaptive investments against floods have already been made in Winnipeg in the Brunkild dike, which has already paid for itself. However, the data on losses from extreme weather events indicate that Canadians have not yet done enough to protect themselves from extreme events. Adaptive responses may also be required in other regions vulnerable to climate change and rising sea levels. An upgrading of existing dikes to protect the lower Fraser valley in British Columbia may be necessary.
14. Careful and proactive planning, especially in infrastructure with a relatively long life, is cost effective. Planners in the town of Milton have recommended spending an additional CAN$7 to 10 million on waterworks to accommodate expected water shortages under climate change. This amount represents an extra 10 to 15 percent of the base cost, and yet is much cheaper than if changes were instituted later. The design of the recently completed Northumberland Strait Bridge included an allowance for a one-metre potential sea level rise due to global warming over the 100-year life of the structure. The added cost of increasing the height of the bridge was small relative to both the total project cost and the possible future costs of countering the effects of a sea level rise.
15. The above examples show that the most important adaptive investments will be *public goods* of this type. But private capital will also have to be adapted through retrofitting or through new investments. In the private sector, optimal adaptations will be determined by the market structure and the prospective yield of its assets. It is important to note that even private adaptations have *social costs,* and the private sector must also be encouraged to incur adaptation costs.
16. The points above (13 to 16) represent examples of *micro level* adaptations, but most of the peer-reviewed literature concentrates on aggregate *macro level* costs and benefits of climate change. For example, for Canada, a warming of 2.5 degrees Celsius in 2060 is estimated to provide significant aggregate positive benefits, based largely on gains in agriculture and forestry. But the estimates are subject to a number of heroic assumptions.
17. The literature review shows that there are sectoral adaptation costs for Canada for coastal protection, due to the expected sea level rise. For the US, there are adaptation costs for the energy sector, forestry and agriculture. There are also some very dated costs of adapting the infrastructure of two cities in the US, but no adaptation costs estimate for infrastructure in Canada. But much of the literature reports "thought experiments" on the costs of adaptation at the aggregate GDP level.

18. From a perspective of “no regrets policy” and the precautionary principle, it is best not to bank on gains from climate change at the aggregate level. Instead, it would be wise to concentrate on the micro level and attempt to estimate adaptation costs. This can be done by (a) relaxing the simplifying assumptions of the theory in the existing literature (b) building a systematic record of physical adaptations and their respective costs, sector by sector. This is exactly what we intend to do.
19. The impact and adaptation costs of accelerated sea level rise have also been examined for Argentina, Nigeria, Senegal, Uruguay and Venezuela. For each country, they assess the level of vulnerability, the per unit cost of beach nourishment, sea walls and harbour upgrades, and the appropriate mix of coastal defence measures depending on the response option chosen.
20. Perhaps the most important single international effort to study adaptation costs has been carried out in the United Kingdom. Their efforts deserve careful monitoring for possible lessons for Canada. Some continuous consultations with the UK could be beneficial for Canadian researchers.

General Conclusion

The review of the literature shows that a consistent methodology for estimating adaptation costs at the micro level does not exist. What does exist is a methodology that regards climate change as a marginal project. This methodology is conceived at a high level of abstraction and the key assumptions need to be relaxed. This can be done systematically, by using a consistent micro level approach and a common data collection protocol, and making the estimates of adaptation dependent on climate change scenarios, "downscaled" for specific local census subdivision levels. ***Thus the estimates of adaptations costs must depend on climate change scenarios, and not the highly abstract assumptions that now characterize the existing literature.*** *At the end of the five years of research, it should be possible to have disaggregated benchmark adaptation costs for all sectors of the Canadian economy. Thus, individual households, private firms and public agencies will have these benchmark costs that they can take into account in order to protect themselves from the adverse impacts of climate change. A well-prepared government is one that has a common template for the estimation of the adaptation costs, and ready information for all stakeholder groups. The work carried out here in Canada can then be offered to other IPCC countries for possible adoption and modifications required for specific countries.*

Introduction: Impacts and Adaptation

The "Canada Country Study" (1998) provided Canadians with a nation-wide assessment of what was known at the time about the potential impacts of climate change on Canada and how we might respond and adapt to these impacts. To date, most of Canada's domestic actions on climate change have focused on mitigation; acting to slow the warming trend by reducing greenhouse gas (GHG) emissions and by similar measures seems to have been a major preoccupation in policy. However, adaptation activities have assumed an increased role in Canada's response to climate change.

Distinct from mitigation, adaptation involves taking action to minimize the negative impacts of climate change or taking advantage of new opportunities that may arise. Canada could experience a level of warming in the decades ahead that could increase stress on a whole range of Canada's natural capital assets as well as human-made capital that includes all public infrastructure as well as buildings, dams and reservoirs. This stress will be felt in the country's water resources, fisheries, forests and agricultural lands. Other resource-based areas of the economy, such as the energy industry, and tourism and recreation industries, may also be affected. Certain parts of urban infrastructure, transportation and utility networks, public health and emergency response systems may require expansion and upgrading. Thus, we look to adaptation strategies to help soften the negative consequences of increasing temperatures, changes in sea level and changes in precipitation patterns. Adaptation strategies are equally important in lessening the negative consequences of increases in climate variability and the occurrence of extreme events that may accompany climate change. Clearly, adjusting to new weather patterns will be difficult and, potentially, will be very costly. In some cases, adaptation may not be a viable option.

There are a number of dimensions to the adaptation process that need to be costed in order to guide the policy making process. Some are easier to identify than others; firms may incur increasing or decreasing costs of production in particular sectors or particular regions, depending on how climate change affects them. In addition to production costs, both the private and the public sectors will have to make investments that make the private capital stock and the public infrastructure more resilient to extreme climatic events. To respond appropriately, the general public should become more aware of the possibility of extreme events such as floods in the spring, heat waves in the high summer, freezing rain or ice storms in the winter. Thus, the general public may incur costs of precautionary purchases.

The estimation of costs and benefits is best carried out at the local and sector levels, or at the *microeconomic level*. *Macroeconomic* approaches yield aggregate estimates of the net impact on the national economy but these are of little value at the specific location, sector or regional level. Macroeconomic models are still unable to include non-market accounts in the standard measures of economic inputs and outputs at the sectoral level and yet these aspects may represent the most significant costs of climate change in Canada. Climate change will affect a large array of natural processes that, in turn, will affect our daily lives. Most of the impacts and the effectiveness of future adaptations are still not known, or are highly uncertain and difficult to translate into costs and benefits, and value judgements are necessarily built into any assessment. Although monetary valuation is highly contentious (Vatn and Bromley in Bromley, 1995), it is one way to represent changes in wellbeing. A comprehensive valuation of impacts and/or adaptive responses is a daunting task. Assigning monetary values to the changes will push economic valuation techniques to their limits, and quite possibly beyond (Fankhauser, 1995).

A critical review of the current literature on the costs of adapting to climate change is the first step in the process of estimating such costs in Canada, as it will serve to focus and guide this new research. To this end, the literature review is presented in four distinct, but related, parts.

In Part One of the literature review, we will use United Nations Environment Programme's (UNEP) assessment of the state of the art in the estimation of adaptation costs (UNEP, 1998) as a jumping off point. One of the primary aims of chapter five of the UNEP publication ("Adaptation Costs: A Framework and Methods") is to elaborate on the conceptual framework developed by Fankhauser (1997; in Smith, *et al.*, 1996) for defining and estimating adaptation costs. UNEP attempts to make this framework more general and addresses some of the associated issues that will need to be resolved in future studies. An interpretation of the modifications to the Fankhauser framework leads us into Part Two of the literature review, in which we critically evaluate conventional economic methods as employed in Fankhauser and in Mendelsohn (2000). Part Three presents some empirical estimates that have been generated for the Canadian economy and examines, in more detail, some of the sectoral studies mentioned in Part One. In Part Four of the review, we synthesize the findings of the previous two parts for costing adaptation to climate change and suggest some concrete research tasks for the next few years.

Part 1: An Examination of Adaptation Studies

According to UNEP (1998), the clearest conceptual statements about adaptation appear in Jepma, *et al.* (1996) and Carter, *et al.* (1994). Both studies make the important distinction between adaptation that occurs in the absence of government policy (that adaptation which would have occurred anyway) and adaptation that requires deliberate policy action. According to UNEP, the Carter, *et al*. study is more useful, since it casts the first type of adaptation in terms of built-in or autonomous responses, hence providing a motivation for this type of passive action. They also emphasize the need to distinguish between adaptation actions that are market driven and those that are additional actions.

The distinction between so-called passive and active adaptation is important. It recognizes implicitly that even if governments do nothing to mitigate climate change or adapt to its effects, economic agents will still have some incentives to offset the impacts of climate change, once the changes have been detected. Unfortunately, adaptation costs are neither operationally defined, nor estimated, in the Carter, *et al.* study. This is the great gap in the literature on adaptation. Various authors have proposed frameworks for differentiation between forms of adaptation and for developing procedures for evaluating measures (Smith and Lenart, 1996; Tol, *et al.*, 1998); however, these costs are not defined and no specific methodology is spelled out.

Similar types of adaptation typologies have been developed in Smit (1993); Ringius, *et al.* (1996); Titus (1990); OTA (1993); Smith and Lenart (1996); Toman and Bierbaum (in Smith, *et al.,* 1996) and Fankhauser (1997; in Smith, *et al.,* 1996). Almost all of these studies emphasize the differences between adaptation actions taken autonomously, and the actions that are taken in advance of, or after, the change in climate. They propose methodological steps for assessing adaptation to climate change, including the use of cost-benefit assessment. However, as UNEP points out, with the exception of Fankhauser, there is no further discussion of cost concepts, definitions and methodologies.

UNEP is highly critical of sectoral level studies contained in the individual chapters of Working Group II Report (Intergovernmental Panel on Climate Change, 1996). First, in almost all cases, the studies in this report ignore autonomous adaptation and its associated economic costs. Some studies of agricultural impacts, using only crop models, focus on how changes in temperature and precipitation affect crop yields. In these studies, the impacts simply do not include adaptation. Other studies focus on the economic impacts of climate change on the sector, sometimes using market models (Adams, *et al.*, 1993) that take into account some, but not all, forms of autonomous adaptation.

Second, and equally important in our view, is that in these studies the treatment of adaptation tends to concentrate on measures whose sole objective is to offset clearly discernible climate change impacts. These include the construction of dikes to counter sea level rise and crop substitution to maintain agricultural productivity. We are in agreement with UNEP that this approach ignores the fact that adaptation is a more general process involving the substitution of many inputs and outputs in response to changes in environmental conditions.

Finally, UNEP notes that, except for studies that assess the costs of protecting coastal areas from sea level rise, there is very little information on the costs of climate adaptation; costs are only addressed explicitly in chapters on the oceans, an area where the role of adaptation is limited.

The state of the art, with respect to sectoral adaptation, has been surveyed by Tol, *et al.* (1998). The authors identify four types of approaches for modelling adaptation that appear in the literature:

1) No Adaptation, which is unrealistic and only serves as reference point
2) Arbitrary Adaptation (both autonomous and additional)
3) Observed Adaptation (the use of spatial and temporal analogues to examine how different societies have adapted to climate variability in the present or past)

4) Modelled or "Optimal" Adaptation (the use of economic market models to predict how humans will behave when climate changes)

UNEP underlines the fact that most of the studies regarding sectoral adaptation fall under the heading of optimal adaptation. This approach is based on simple convex optimisation, where the optimal solution is defined to be "efficient" (Mendselsohn, 2000). It assumes that the benefit function is concave and is twice differentiable, so that marginal benefits decline with increasing adaptation. It is also assumed that the cost function is convex and that the costs increase at an increasing rate with increased adaptation. Thus at the optimum, the optimizing economic agent adjusts to climate change by equating marginal benefits to marginal costs. This is what Mendelsohn (2000) calls an "efficient solution." Tol and his co-authors regard this as the "ideal" approach to assessing adaptation because it can be used to project the economically efficient levels of private (autonomous) adaptation and public (additional) adaptation, given specific changes in climate. While this sort of approach is instantly recognizable to economists, it is, in our view, misguided, and subject to unrealistic assumptions. Our main reservation is that this approach treats climate change like any other additively separable, *marginal project,* such as a power station, or a bridge, or a deli counter in a supermarket. A critique of the approach from a deeper theoretical standpoint forms the content of the second part of the literature review. First, however, we will review what UNEP has to say about other sectoral studies and about the Fankhauser framework for estimating adaptation costs.

There is a fairly large body of literature about the value of the economic impacts of climate change that takes adaptation into account; however, in UNEP's view, these works fall short of specifically estimating the costs and benefits of adaptation. This literature is best represented by studies such as that by Yohe, *et al.* (1996) of the economic value of damages due to sea level rise and the work of Adams, *et al.* (1993) on the US agricultural sector. Mendelsohn and Neumann (1999) contains estimates of the value of damages due to climate change in the US for seven different impact sectors (agriculture, forests, water resources, sea level rise, energy, recreation and commercial fishing). Several of these studies (such as the study by Hurd, *et al.* in Mendelsohn and Neumann, 1999) include the effects of climate change on the supply and allocation of US resources, including both market and non-market adaptation.

These studies use economic market models that contain supply and demand curves that are linked to climate variables. Thus, changes in monthly temperature and precipitation, for example, induce changes in relative prices of inputs and outputs. This, in turn, affects the relative profitability of various goods and services in markets and leads to different levels of input use and commodity production. The resulting levels of profits after these adjustments occur are higher than if the adjustments did not occur. The adjustments in input and output levels in response to climate-induced changes in relative prices are in the broadest sense adaptive responses to climate change. It is important to understand that these studies do not explicitly report adaptation costs; they report the imposed costs of climate change, measured as the difference between net social benefits, with and without climate change. While these studies take into account a wide range of normal market adjustments, they do not generally include estimates of both benefits and costs associated with adapting from one climate scenario to another. There are a few scenarios, for example sea level rise (Titus, *et al.*, 1991; Fankhauser, 1995; Yohe, *et al.*, 1996; Yohe and Cantor in Rayner and Malone, 1998), where the costs of specific adaptation measures, such as building sea walls and retreat, have been estimated.

UNEP notes that there is a drawback in an approach linked to optimizing behaviour. Optimal adaptation may not imply economic efficiency in countries where markets operate poorly or where the economy contains a large informal sector where transactions of goods and services are based on non-market objectives. There are also larger theoretical issues not recognized by the UNEP critique. UNEP criticizes the Fankhauser framework from the standpoint of making the framework more general. We return to the larger theoretical issues in this section.

Fankhauser's conceptual framework for estimating adaptation costs involves defining the optimal level of adaptation in a region where the amount of climate change (and implied level of global mitigation) is not under national control. To find the optimal level of adaptation, Fankhauser's analytical model uses the approach of minimizing the sum of the two cost elements, adaptation cost and unmitigated damage cost, and assumes that the level of damages due to climate change and the level of global mitigation are both fixed. Both of these costs depend on the level of adaptation; however, adaptation costs increase as the level of adaptation increases, while the level of unmitigated damages decreases as adaptation increases. In this framework, adaptation actions are justified as long as the additional costs of adaptation are lower than the additional benefits from reduced damage levels. The level of adaptation is optimal where the last dollar spent on adaptation just equals the reduction in climate change damages achieved by this expenditure. This is nothing but equating marginal benefits (MB) with marginal costs (MC). We shall refer to this as the MB = MC rule.

It is clear that this rule is the guiding principle that will determine the quantity of adaptation implemented, but it needs explanation. The guiding rule is the same as the one that is used in environmental clean-up and remediation. In remediation, this guiding rule treats the environmental damage as marginal to the economy and the rule determines that the optimal expenditure on remediation is reached when the marginal cost of remediation equals the marginal benefit of that remediation, or MB = MC.

First, note that the damage is marginal, such as an oil spill in an isolated river or stream. *Complete* cleanup is never indicated by the MB = MC rule. Thus, the clean-up is a function of the prevailing technology and the prevailing prices of inputs into clean-up. What future damage the residual spill could do is thus ignored in this rule.

Second, the sample rule (MB = MC) is applied to determine the optimal quantity of adaptation. This means that the impact of climate change is seen as being marginal and that each "project" (such as a bridge or a harbour) should be retrofitted by the MB = MC rule. The key issue here is the valuation of marginal benefits and the valuation of the marginal costs, or the "valuation criterion". A critical evaluation of the valuation criterion is the subject of Part Two. As stated previously, UNEP identifies some weaknesses in Fankenhauser's framework for costing adaptation, to which we now turn.

Fankhauser identifies five different types of costs that can be defined for different climate states:

1) Adaptation costs, which are the costs of resources forgone by society to undertake adaptation measures both in the baseline and future climates
2) Climate change damages, which are the value of the extra damages that occur exclusively because of climate change (zero in the baseline scenario)
3) Ordinary climate damages, which include the adverse effects associated with the current climate (all climate related costs that would occur if there were no climate change)

4) Other relevant costs, which are the indirect costs that result from taking an adaptation action

5) Imposed costs of climate change, which are defined as the difference in overall costs between the climate change and the reference scenario, taking economically optimal adaptation into account.

UNEP sees two main problems with Fankhauser's framework. First, it is not general enough and it focuses primarily on adaptation measures whose sole objective is to counter the effects of climate variability and change. Second, many of the above cost definitions require that one is able to quantify specific adaptation costs in both a reference scenario and in a climate change scenario in order to estimate the difference between the two. This is simply not possible for types of adaptation actions that include more general forms of input and output substitution.

UNEP purports to build on Fankhauser's framework to arrive at a framework that allows for benefit-cost comparisons to be made between adaptation benefits and costs and mitigation benefits and costs. They emphasize that their framework is consistent with traditional approaches for estimating the imposed costs of climate change, as presented in a number of recent studies about the economic value of the effects of climate change in specific sectors of developed country economies. According to UNEP, this means that sector models that have been used to estimate the imposed costs of climate change can also be used to estimate the adaptation benefits, costs and net benefits. This can be done by creating a new scenario to reflect the altered climate with adaptation to the base case. The benefits, costs and net benefits in this scenario are compared with the same model outputs from a scenario that includes climate change and allows adaptation to the altered climate.

According to UNEP, Fankhauser (1997; in Smith, *et al.,*1996) uses an institutional and not an economic definition of adaptation. UNEP favours a definition that

> "…includes actions that take the form of projects and policies, but also embrace a wide range of behavioural adjustments that economic agents undertake directly, in response to observed or expected climate impacts, and indirectly, as a result of climate-induced changes in relative input and output prices." (UNEP, 1998, p.102)

In their view, this type of definition embraces both autonomous adaptation and adaptation strategies undertaken by government. This definition emphasizes the role of markets and market forces. Thus, adaptation measures include building and modifying sea walls and reservoirs, abandoning coastal properties, adjusting planting and harvesting dates, altering input use, crop switching in agriculture and forestry, modifying reservoir operating rules, constructing early warning systems for climatic hazards and adjusting insurance premiums. UNEP stresses that adaptation also includes learning about climate change and disseminating this information to potential users.

According to UNEP, the cost definitions of the Fankhauser framework are useful for analyzing projects and policy measures, such as sea wall construction, that are directly focused on adapting to climate and that have "price tags" on them. However, this approach does not work for behavioural actions. It is this perceived deficiency that UNEP seeks to remedy. UNEP alters the framework by altering Fankhauser's accounting structure. The idea is to create a framework based more on measuring benefits and costs due to changes in climate than on defining costs and benefits in each climate state. In the view of UNEP, it then becomes possible to separate the effects of climate change from those of adaptation actions. The cost and benefit concepts would then be defined as follows:

- Climate change damages (costs) are the net costs to society of climate change if no adaptive measures are taken. These equal the sum of net adaptation benefits and the imposed costs of climate change.

- Adaptation benefits are the value of the climate change damages avoided by adaptation actions.
- Adaptation costs are the value of the real resources society gives up (opportunity costs) to create adaptation benefits.
- Net adaptation benefits are the value of adaptation benefits minus adaptation costs.
- Imposed costs of climate change are the net costs to society of climate change if adaptation actions are taken. These costs are the difference between climate change costs and net adaptation benefits

While UNEP points out some deficiencies in Fankenhauser's framework, it explicitly accepts the MB = MC rule for determining the optimal quantity of adaptation. Unfortunately, UNEP fails to recognize that the impacts of climate change are likely to be global in two senses; they are global in the sense that the impacts will eventually permeate each and every sector of the economy and they are global in a purely spatial sense in that the impacts of climate change will affect the entire biosphere. Thus, even if, as expected, the impacts of climate change are spread over 50 to 200 years, the impacts cannot be treated as being marginal. They are marginal only if a decision-maker adopts a very short-term horizon of three to four years. In the next section, we consider the theoretical foundations of the MB = MC rule. As stated, this refers to how the marginal costs and marginal benefits are valued.

Part 2: Costing Methodology

Assigning dollar costs to climate change adaptation in Canada is more than an exercise in accounting and arithmetic. The costing methodology that is adopted must stand on certain theoretical underpinnings or one is simply not engaging in scientific inquiry. Of course, without sound science there can be no effective social policy-making. This part of the literature review is concerned with some theoretical issues in actions designed to adapt to climate change. These issues relate to the economic valuation of the impact of climate change and the attempted determination of adaptive response based solely on monetary benefits and costs. By convention, this approach restricts the amount of information simply to consumer satisfaction (in terms of utility, measured in money) and reduces environmental policy to be determined by a single and imperfect metric. This metric is common to both conventional economics and ecological economics. This part of the literature review is organized as follows:

- Section 2.1 is a brief critique of the so-called "ecological approach" to the environment.
- Section 2.2 considers the conventional economics approach to global climate change, which relies on specific functional forms when the basic economic model is not structurally stable.
- Section 2.3 relates the issue of structural stability to the question of an invariant measure of value in economics, as it turns out that only special assumptions about human behaviour guarantee both structural stability and an invariant measure of value. The requirements for an invariant measure of value are stated as the Chipman-Moore conditions.
- Section 2.4 discusses the marginal utility of money and the Chipman-Moore conditions.
- Section 2.5 discusses the problem of structural stability of the basic economic (general equilibrium) model in greater detail.
- Section 2.6 concerns lessons for environmental policy, and contains a non-technical summary of the above sections.
- Section 2.7 discusses the social rate of discount.
- Section 2.8 discusses an alternative approach, which we might call the asset valuation approach, in which the assets are natural capital, and their ecological flows are the "dividends" in perpetuity; and the appropriate management of this portfolio of natural assets

includes the preservation of future options through the conservation of natural capital; and finally,

- Section 2.9 presents the general conclusions for entire section.

2.1: Value in Ecological Economics

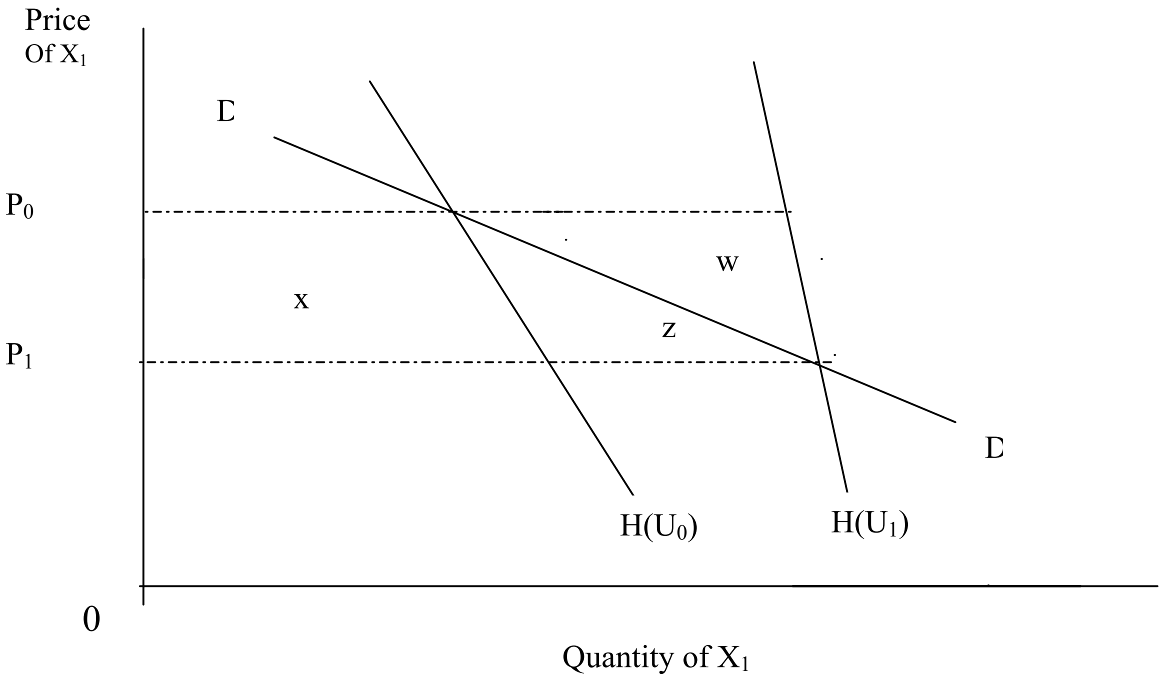
The vast majority of the economics profession would argue that the wellbeing of the human agent is of primary importance and that therefore economics, which maximizes the satisfaction of human wants, should play the central role in all decisions, including decisions affecting the environment. The ecosystem can be taken into account as a constraint in the maximizing process. In this way, all the requirements of the ecosystem can be systematically incorporated without sacrificing the fundamental goal of all human activity, which is maximizing human wellbeing, however defined. It could then be argued that the economics literature has successfully incorporated natural resource management and that even the notions of strong and weak sustainability (Pearce, *et al.,* 1989) can be integrated into conventional economics. Furthermore, a sub-branch of economics called "ecological economics" is now well established as a discipline, with its own societies all over the world and with its own journals. It could be argued that the International Society of Ecological Economics has done much to integrate ecosystems into economics.

However, much of what is called ecological economics is indistinguishable from "standard" neoclassical economics. A leading proponent of ecological economics and the founding editor of the journal called "Ecological Economics" is Robert Costanza. He has also edited a much-used textbook called "Ecological Economics" (Costanza, 1991). Let us take as an example of ecological economics, the article published in Nature (1997) by Costanza and his co-authors.

Costanza, *et al.* attempt to put a monetary value on all the ecological services provided by the biosphere. To accomplish this, they divide up the biosphere into 17 biomes, and place a value on each. They then conclude that the value of the 17 biomes is equal to 1.8 times world gross national product (GNP). Costanza, *et al*. use the standard consumer surplus (CS) as a method of valuation. CS is the benefit that the consumer derives from a particular good. For a market good, it is the price that the consumer would be willing to pay for the good, minus the price actually paid. However, the numerical estimation of CS requires the use of a particular utility function to derive the demand curve for a "representative consumer". This technique has obvious difficulties for a global valuation. Unfortunately there is also a conceptual confusion in their work. While they claim to be using willingness-to-pay (WTP) as the standard of value, they refer to the cost of the *loss of a particular biome* as the value of it. The loss value is conceptually distinct and is called willingness-to-accept (WTA). In the above case, WTP would be an appropriate measure of value if the individuals surveyed were asked what they would be willing to pay to purchase additional biomes. As indicated in the name, WTA is the willingness to accept compensation for an environmental good that is lost. The difference between WTP and WTA is illustrated in the following example:

If a factory, which will pollute the air, were to move to an area previously free of pollutants, WTP would be the inhabitants' willingness to pay to clean the air and WTA would be what the inhabitants were willing to accept in compensation for the fact that they now have polluted air. Indeed, in economics, there are three distinct measures of value, CS, WTP and WTA, which are equivalent only under very special circumstances (see below). For normal goods, it can be shown that WTP < CS < WTA. Figure 1 illustrates these differences. The area under the Hicksian Compensated Demand Curve $H(U_0)$ labelled x is the WTP. The area under the Marshallian Demand curve, D (x + z) is the CS. The area under H(U_1) is composed of x + z + w is the WTA.

Figure 1: The Relationship between WTA, CS, and WTA



(Hanley and Spash, 1993, p.40)

There are several reasons why the WTA is generally greater than the WTP, namely:

- Individuals tend to be "loss averse"
- WTA bids are not constrained by income
- Few potential substitutes inflate the value of WTA
- Due to risk aversion, individuals tend to overvalue WTA and undervalue WTP

The estimation of any of the three measures of value requires the use of a specific functional form of a demand function. The choice of the functional form is usually arbitrary, and varying the functional form could change the results dramatically. All of this is very well known to economists.

For environmental amenities or ecological services, there are no markets and therefore no market *demand curves.* Economists consequently use survey methods or some other surrogate to estimate a demand curve and determine the change in CS as the potential gain associated with any proposed public action, such as climate change adaptation. For some ecological services, which are clearly valuable to society, even the survey and surrogate methods may not be possible, as the ecological services are provided "free" by the biomes. In such a case, it is of interest to find some measure of what society would *lose* if the biome were destroyed. This approach requires WTA as the appropriate measure, as the authors imply towards the end of their article. Like WTP, WTA estimates can only be done at a higher level of abstraction, where the numerical estimate is again highly dependent on the *choice* of the functional form of the demand curve and the estimate of WTA could vary by a factor of two or even four. For each ecological service provided by a different biome, the abstraction must necessarily be at a different level. Each valuation may be a legitimate thought experiment, taken individually, but each remains nothing more than a mental exercise. But to add up each diverse mental exercise and to come up with a total value of 1.8 times world GNP is a gross error.

As a mental exercise, it is legitimate to estimate the <u>marginal social opportunity cost</u> (MSOC) of a particular ecological service of a particular biome. But as this value is "at the margin," it requires the assumption that the *rest* of the price system is constant, or as economists say, in equilibrium. The theoretical justification is as follows: if the economy was perfectly competitive and in equilibrium, then the WTP measure and the MSOC measure should be identical, at least in theory. Nevertheless each MSOC value (or the WTA value) is still a thought experiment; a mental exercise subject to important *ceteris paribus* assumptions. As the assumptions will vary for each mental exercise, it is not possible add them up as a homogeneous quantity and value the biosphere as being 1.8 times world GNP.

We have no doubt that the authors were trying to draw the attention of decision-makers to the importance of the 17 biomes and the extent to which human society is dependent on the proper functioning of various cycles, such as the hydrological cycle and the carbon cycle, and the interdependence of the ecosystems. Indeed, if they can add up the value of the 17 biomes, one might ask why did they stop there? Why not put a monetary value on the moon, the loss of which would disrupt ocean tides? Why not put a monetary value on the sun too?

No economist in his or her right mind would try to put a monetary value on the moon or the sun. These celestial bodies are not *marginal* to the world economy. The 17 biomes determine the very existence of life itself on this planet. Therefore they are not marginal and putting a monetary value on them is simply absurd.

The absurdity does another disservice. First, it makes a mockery of environmental protection. Second, it hides important intergenerational ethical issues. It seems to suggest that difficult ethical issues can be settled simply on the basis of a one-dimensional monetary metric. The protection of the biosphere for future generations is an ethical matter, not a monetary matter. This, incidentally, is clearly recognized by UNEP (1998).

The above critique of Costanza, *et al.* (1997), who is a leading ecological economist, shows that, in essence, ecological economics is no different from conventional economics, which also treats environmental remediation *at the margin*. It would similarly treat adaptation to climate change at the margin. But conventional economists are unlikely to add different thought experiments, as if each was a homogeneous quantity. The approach of conventional economics is much more subtle. The next section shows this.

2.2: Value in Conventional Economics

The fundamental approach of maximizing consumer satisfaction requires assuming a "representative agent." This approach is individualist, anthropocentric and completely unequal to challenges such as global climate change, ozone depletion and large-scale land and water pollution. The representative agent approach, in turn, dictates a *maximand* in which the only information that is allowed is the utility (or consumer satisfaction) of that representative agent (for examples, see Sen 1977a, 1977b, 1979a, 1979b). The representative agent is assumed to have an exogenously given set of preferences over goods, not only today, but over *all* goods and also at *all* times. The latter gives rise to *time preference,* or a rate of discount. The entire economy is seen as an auction market in which "true" prices for all goods and all environmental services emerge; where they do not emerge or where the actual prices deviate from the "true" prices, the economist can "correct" these by various techniques, or can "invent" them by survey or other implicit methods. In all the calculations carried out within the above framework, the optimum is obtained by balancing the marginal benefits to the representative consumer compared with the marginal costs to the consumer. The logical consequence of the above is that the *optimal level of pollution is never zero*. As a result of the acceptance of the concept of time preference, all flows of money (as the only *numeraire* allowed in economics) are discounted. But discounting of necessity allows only short time horizons, not 500 or 1000 years.

The poverty of the conventional economic approach to the environment can be illustrated by considering the work of Nordhaus (1994), and Nordhaus and Popp (1997), but as Nordhaus has been heavily criticized by others, only a brief restatement of his method and his results is necessary. Nordhaus (1994) maximizes the discounted value of the consumption of a representative consumer, subject to output produced by a constant returns to scale Cobb-Douglas production function. The production of output generates GHGs, which in turn leads to losses in output. This is a standard optimal growth exercise, which is also no more than a thought experiment. A thought experiment is subject to all sorts of caveats and, no doubt, Nordhaus is aware of that. In spite of the limitations of thought experiments, we get, from Nordhaus, an "optimal policy" recommendation to reduce GHGs by 11.1 percent in 2025 and by 13.4 percent in 2075. These reductions are relative to "uncontrolled emissions" that would have occurred if no curbs on emissions had been placed.

As stated above, Nordhaus's work has been heavily criticized for some specifics of his model. For example, Ekins (1996) argues that Nordhaus ignores the benefits of reductions in other noxious substances that would accompany reductions in CO_2 emissions. Price (1995) argues that Nordhaus overestimates the CO_2 uptake by oceans. Chapman, Suri and Hall (1995) argue that Nordhaus underestimates the rise in temperatures. Neumayer (1999) does a comprehensive critique and attacks the central assumption inherent in Nordhaus, which is the assumed substitutability between natural capital and man-made capital. Neumayer also does an excellent job not only of reviewing the work of other critics, but also of dealing with both intergenerational and intragenerational equity issues, which are the key to the whole debate over global warming. Most critics fail to realize that Nordhaus' work is nothing more than a thought experiment which uses specific and special functional forms: he uses a logarithmic utility function for the representative consumer and a Cobb-Douglas production function. These are specific functional forms and different functional forms will yield different results.

When is it possible to use a production function? What are the necessary and sufficient conditions for the existence of a production function? Do Cobb-Douglas forms satisfy these conditions? What is the merit of a particular set of functional forms? One could perform a whole battery of thought experiments, with a variety of functional forms of the utility function and the production function, and each experiment will produce a different “optimal policy”. Is there any guarantee that these optimal policies would converge? Absolutely not; each thought experiment reflects its special character. And we have said nothing about the parameters used: the choice of prices of land (Ayres and Walter, 1991), the choice of agricultural costs (Cline, 1996), additional arguments in the utility function of the representative consumer (Tol, 1994), or choice of discount rates (Azar and Sterner, 1996). All these choices also determine the so-called "optimal policy.”

What do physicists say about a model when a variety of functional forms do not lead to a convergent result? Let us consider this question in detail. Economists are in general familiar with dynamic stability, but with few exceptions, the implications of *structural stability* are only just beginning to be analyzed. As physicists know, it is structural stability that establishes the degree of generality of a model or, indeed, the domain of validity of any model, including the basic general equilibrium economic model. The concern with structural stability (SS) in nonlinear dynamic analysis is nothing new. Not surprisingly, the concept comes from physics. The Maxwell-Duhem concept of SS (Duhem, 1906; Maxwell, 1877) is that SS is a required property of a model that is *adequate*. A model is adequate in terms of prediction and verification if, for some perturbation within the (relevant) domain of perturbation, the ability of the model to predict outcomes remains intact. If the perturbation destroys the ability of the model to yield sensible results then, according to Maxwell, the model is no good; it is inadequate. In the physical sciences, it would then be necessary to go back and build a better model of the underlying reality that is being studied. In the physical sciences, experimentation is the ultimate criterion of the validity of a model. Unfortunately, experimental verification of the general equilibrium model is impossible; consequently, economists do not feel it necessary to consider an alternative model.

The question of structural stability of the basic economic model is important and is taken up later in this report. It will be shown that structural stability can be assured only if it is assumed that the representative consumer has homothetic preferences[1]. In turn, homothetic preferences also produce an invariant measure of value. Homothetic preferences entail that the utility preferences of an individual do not vary with income. As stated previously, without the assumption of homotheticity, there are *three* standards of value in neoclassical economics: consumer surplus (CS), willingness to pay (WTP) and willingness to accept (WTA). Each can be expressed in terms of money. In a modern neoclassical context, the problem of an *invariant measure of value* has been elegantly restated by Chipman and Moore (1980), to which we now turn.

2.3: The Chipman-Moore Conditions

Chipman and Moore (1980) ask a very important question that goes to the heart of the determination of an *invariant measure of value*, a subject much discussed in the history of economic thought. The general conclusion of this historical debate on an invariant measure of value was that the classical labour theory of value was a special case. In neoclassical economics, it was generally assumed that the problem of reconciling two different measures of changes in value, namely the reconciliation of WTP and WTA, was a "partial equilibrium" problem, which would not arise in general equilibrium analysis. Clearly this is no longer true, even if it ever were the case, as Saari finds that the Chipman-Moore restrictions are necessary for convergence of the price adjustment equation to a zero. It would therefore be instructive to take a closer look at the Chipman-Moore conditions.

The important question that Chipman and Moore ask is the following: under what conditions on preferences, and on admissible pairs of income and prices under comparison, do the Marshallian and Hicksian consumer surpluses yield common and acceptable integral measures of welfare change? In other words, when do the WTP and WTA *coincide,* so as to give a common and an *invariant measure of value?*

The authors provide three possible answers, depending on what restrictions are placed on prices (***p)*** and changes in incomes ***(Y)****:*

CM-1 If there are no restrictions imposed on pairs of prices and income $\boldsymbol{p^1}$, $\boldsymbol{Y^1}$ and $\boldsymbol{p^2}$, $\boldsymbol{Y^2}$, under comparison, then there are *no* conditions under which the Marshallian consumer surplus yields an acceptable measure of welfare change. Nor can consumer surpluses be added to determine if the gainers can compensate the losers (Boadway, 1974).

CM-2 If, in the comparison of $\boldsymbol{p^1}$, $\boldsymbol{Y^1}$, and $\boldsymbol{p^2}$, $\boldsymbol{Y^2}$, a restriction is imposed so that income is unchanged (i.e. $\boldsymbol{Y^1}=\boldsymbol{Y^2}$), then the Marshallian consumer surplus is an acceptable measure of welfare change if and only if the underlying preferences are homothetic[1].

CM-3 In the comparison of $\boldsymbol{p^1}$, $\boldsymbol{Y^1}$, and $\boldsymbol{p^2}$, $\boldsymbol{Y^2}$, let $\boldsymbol{p^1_1}=\boldsymbol{p^2_1}$. This means that if income and all other prices are deflated by the price of Commodity 1 in each period, then the Marshallian consumer surplus is an acceptable measure of welfare change if and only if preferences are parallel with respect to Commodity 1. Parallel preferences mean that the Engel curve is vertical and parallel to the axis of Commodity 1.

Furthermore, Chipman and Moore show that the above results also hold if we substitute Hicksian or "compensated demand" for "Marshallian" consumer surplus. Both demand curves hold income constant and show the quantity of goods demanded at different prices. But the Hicksian compensated demand curve isolates the substitution effect of a price increase or decrease by compensating for the income effect. In other words, CM-1 to CM-3 apply to the problem of deriving an *invariant measure of value*. The conditions under which an invariant measure is obtained are restrictive, which makes the invariant measure a very special case. That will become even clearer if we reconsider CM-2 and CM-3 in terms of the marginal utility of income (MUI).

It is simpler to interpret the Chipman-Moore conditions in terms of the marginal utility of income, as this ties in well with the received doctrine of consumer theory.

2.4: The Marginal Utility of Money and the Chipman-Moore Conditions

For clarity, it might be useful to start with some standard notation. Suppose the consumption bundle of quantities is $\boldsymbol{x}=(\boldsymbol{x_1}, \boldsymbol{x_2},\ldots,\boldsymbol{x_n})$, and the consumer's utility function is $\boldsymbol{u(x)}$. Let the price vector be $\boldsymbol{P}=(P_1, P_2,\ldots,P_n)$. From standard optimization, we can obtain the demand functions:

$$x_i = x_i(P_i, Y) \;\; and \;\; \lambda(P, Y) \qquad (1)$$

all of which are homogeneous of degree zero in $\boldsymbol{P}$ and $\boldsymbol{Y}$. Next, define the indirect utility function:

$$U(P, Y) \qquad (2)$$

Suppose we wish to find the welfare impact of a change from $\boldsymbol{Q}^{\boldsymbol{0}}$ to $\boldsymbol{Q}^1$. The change in total utility is given by the total differential:

$$dU = \sum_{i=1}^{n} U_i \, dP_i + U_Y \, dY \qquad (3)$$

The welfare impact (ΔU) of the changes in prices and incomes may be defined as the line integral[2]:

$$\Delta U = \int_{Q^0}^{Q^1} [\sum_{i=1}^{n} U_i \, dP_i + U_Y \, dY] \tag{4}$$

From the Slutsky matrix and the envelope theorem, we can substitute and rewrite the above equation in terms of the marginal utility of income as the following:

$$\Delta U = \int_{Q^0}^{Q^1} [\sum_{i=1}^{n} (\lambda x_i) \, dP_i + \lambda dY] \tag{5}$$

where $\partial U / \partial Y = \lambda$. In general, λ depends on both $\boldsymbol{P}$ and $\boldsymbol{Y}$. So we need some assumptions about the constancy of λ in order to evaluate the integral in the above equation. Following Samuelson (1947), we can try three possible avenues:

1. Suppose we assume that λ is constant for all values of $\boldsymbol{P}$ and $\boldsymbol{Y}$. This leads to a contradiction, as $\boldsymbol{U_y}$ is homogeneous of degree -1 in $\boldsymbol{P}$ and $\boldsymbol{Y}$. Therefore λ cannot be constant for all values of $\boldsymbol{P}$ and $\boldsymbol{Y}$.

2. Suppose we assume that λ is invariant to all changes in all prices, i.e.

$$U_Y(P,Y) = \sigma(Y) \tag{6}$$

This equation is then equivalent to homothetic preferences, or CM-2 above. Thus we can reinterpret CM-2 as the assumption that the marginal utility of income does not change with changes in prices.

3. The third possibility is to assume that λ is independent of all income and all prices except Commodity 1, the numeraire commodity. Indeed this is how Hicks interpreted Marshall's concept of consumer surplus. With this assumption, we can write:

$$U_Y(P,Y) = \rho(P_1) \tag{7}$$

The above equation is equivalent to parallel preferences, or CM-3. We can reinterpret CM-3 as the assumption that the marginal utility of income is independent of the level of income and all prices except that of Commodity 1.

Thus we have shown that the neoclassical invariant measure of value is obtained only by assuming the constancy of the marginal utility of income, either with respect to all prices, so that it is a function of income alone, or the marginal utility of income is independent of all income and all prices except one. The assumption of complete independence of all income and all prices is not possible because that involves a contradiction. The constancy of marginal utility of income means that it is the same for both a rich person and a poor person, an implicit and unintended interpersonal comparison of utility. In a sense, this makes the utility approach dictatorial, which is, again, an unintended consequence. The problem arises from the single dimensional utilitarian approach, in which it is assumed *exogenously* that each individual must maximize his or her utility rather than leave the decision to the individual to pursue her own goals, whatever they may be. The requirement that each individual must maximize his or her utility is imposed from the outside. It is this exogenous imposition of utilitarianism which is objectionable to theorists like John Rawls (1971)[3].

The above conclusion on the required conditions for an invariant measure of value suggests that either way it must be assumed that the marginal utility of income is constant. Alternatively, we may say that the invariant measure of value exists only when severe restrictions are placed on the nature of the underlying consumer preferences. This really makes the neoclassical criterion of value a special case. In consumer theory, the constancy of the marginal utility of money can be locked up in a *ceteris paribus* clause. But if the same restrictions are necessary in general equilibrium analysis in order to have the price adjustment differential equation reach equilibrium, then clearly the theory of value rests on very tenuous grounds.

2.5: The Single Dimension and Structural Stability of the Basic Economic Model

It turns out that the restrictive nature of preferences needed for an invariant unidimensional measure of value are also required for the structural stability of the basic economic model. Let us show that in detail.

It is assumed that the basic model is very general indeed and that it is not restricted to any particular number of goods or any particular number of traders, or to a particular structure of preferences, and that only a few innocuous axioms are involved. It is this assumed generality that this report seeks to refute; in fact, studies in the structural stability of the basic model show that it is very special and not so "general" at all.

To begin, suppose that the *number* of commodities, and hence of prices, in the excess demand function in the basic model were restricted to being less than or equal to three. Let the price adjustment process be governed by the differential equation:

$$\dot{p} = z(p) \qquad (8)$$

where $z(p)$ is the excess demand function, and p is the price vector. Then it is well known that the initial conditions of the above differential equation will in general not pose any difficulty. When the number of commodities is greater than three, not only do initial conditions matter, but the evolution of the system (last equation) can become unpredictable. However, a quick review of some mathematics is necessary before proceeding.

Any dynamical system has three kinds of behaviour (Dore, 1993). These are:

(a) An unchanging (or equilibrium) state

(b) A behaviour that repeats itself periodically (called a *limit cycle*) and

(c) Behaviour that is complex or chaotic.

In terms of the phase space of the above differential equation, (a) above translates into a *fixed-point attractor*, (b) becomes a periodic attractor (i.e. a stable limit cycle). If the number of commodities $n > 2$, then all behaviour will be either a fixed-point attractor or a periodic attractor. Together, these are called *simple attractors*.

Now, if the last equation has a number of agents (n) greater than three and is nonlinear, then the higher dimensional analogue of a periodic attractor (when it exists) is called a *strange attractor*. But the trouble is that there may be more than one strange attractor, and a very slight perturbation in the initial condition may cause the behaviour to “switch” from one strange attractor to another.

As mentioned earlier, the early proponents of the basic economic model relied on some fixed point theorem, such as the Kakutani theorem, to assert the existence of a "zero" (that is, a point where all excess demands $z(p) = 0$). Thus, equilibrium is said to exist but the manner in which these prices tend towards that equilibrium is not spelled out[4]. Furthermore, the existence of equilibrium is guaranteed only with an infinity of traders or agents. If the number of agents is finite, then according to the Gibbard-Satterthwaite theorem (Gibbard, 1973; Satterthwaite 1975), it would be possible for agents to collude and force the outcome away from a competitive equilibrium. But, with an infinity of agents, the dynamics of price adjustment are not tractable. The rest of this section therefore considers adjustment of prices when both the number of agents and the number of commodities is finite.

Suppose we ignore the Gibbard-Satterthwaite theorem. With a finite number of commodities and agents, can we say that the invisible hand story holds, and do prices tend towards some local attractor? Even if it is assumed that *z(p)* are homogeneous of degree zero and that Walras' Law holds, and it is further assumed that all chaos generating properties are ruled out, even then additional restrictions will have to be imposed on *z(p)*. Specifically Sonnenschein (1973) provided the additional restrictions that would be required, and Mantel (1972) improved on it. Debreu (1974), however, simplified the proof of this theorem on excess demand functions. The theorem states, roughly, that for n > 2 and some neighbourhood of the price, the mapping is "onto" if and only if the number of agents j is not less than *n*, the number of commodities. In other words, if $j=n$, then there is no guarantee that prices would converge even to some limit cycle. This would be true even if equilibrium existed.

Other approaches of putting even more structure on the last equation have been tried. Replace the last equation by

$$\dot{p} = M(z(p), J_p(z)) \tag{9}$$

where *M* is piecewise smooth, and such that the dynamics stop if and only if $z(p)=0$, and J_p is the Jacobian of the excess demand functions. This formulation by Smale (1976) requires an enormous amount of information, an obvious contradiction of the informational efficiency of the invisible hand. Let us be clear on the economic interpretation of the Jacobian. It says, for example, how the price of any one good varies with the price of all other goods. For example, how the price of jet turbines varies with the price of chewing gum! Thus all cross partials must be known in advance.

But there is more bad news. Saari (1985) replaced the last equation with a discrete version, and analyzed the minimum conditions on the price mechanism M required to ensure convergence to some equilibrium price vector. He found that for $n > 2$, no mechanism M can guarantee convergence to equilibrium: for any choice of M, there exists a large variety of excess demand functions and a large set of initial conditions for which convergence never occurs. This result has a parallel: according to Saari (1985) the same impossibility holds for numerical methods used to find the real roots of real polynomials. This is also confirmed by Bala and Keefer (1994).

It is a paradox that experiments on the theoretical workings of the invisible hand now show that not "free markets" but *regulated* markets might achieve equilibrium, as shown by Saari and Williams (1986). This entire line of research (Saari, 1992) suggests that apart from technical restrictions, convergence of differential equations of excess demands to a "zero" (i.e. to equilibrium) requires that: (a) the number of agents must be greater than or equal to the number of commodities, and (b) severe restrictions on the nature of preferences must be placed. These restrictions are analogous to the restrictions on preferences that are required by Chipman and Moore (1980) in order to obtain an exact and an invariant measure of consumer surplus, which is the measure and standard of value in neoclassical economics.

Clearly condition (a) above is very restrictive and was unknown until the dynamics of excess demand were investigated, largely by mathematicians who do not have an ideological stake in neoclassical general equilibrium theory.

2.6: Lessons for Adaptation to Climate Change

What do the results obtained above mean for (a) the determination of the economic impact of climate change and (b) the determination of the costs of adaptation to climate change? Let us begin by summarizing the key findings before proceeding.

The above analysis shows that whether the approach is a standard environmental economic approach or whether it is "ecological economics", the fundamental basis of valuation is the same - the technique of valuation is based on some measure of consumer satisfaction, either consumer's willingness to pay (WTP), or consumer surplus (CS), or consumer's willingness to accept (WTA). The divergence between WTP and WTA could be in the interval $(0,\infty)$. These three measures of value coincide only under specific assumptions about preferences. In general, we know that WTP < CS < WTA. The above analysis was confined to price changes only. If quantity changes are considered, then the conclusion is further strengthened with WTP = 0 and WTA = ∞. Further details may be found in Randall and Stoll (1980) and Hanneman (1991). This consumptionist approach requires the assumption of a representative consumer, who is assumed to be maximizing his/her utility. The utility maximizing model yields a demand curve. A measure of this consumer's wellbeing (or "advantage") is the integral under the demand curve. In order to get an invariant measure of value, it is necessary to assume that this representative consumer has "homothetic preferences". This is incidentally patently false because the best-established law in economics (called Engel's Law) shows that preferences are *not* homothetic. Specifically, Engel's Law states that total expenditures on food, as a share of income, falls as income rises. Furthermore, in order to obtain a numerical estimate of WTP, CS or WTA, one needs to use specific functional forms of the demand curve. Thus, any numerical estimate of value will depend on the specific functional form used to represent the demand curve. Experimenting with a variety of functional forms does not lead to a convergent optimal policy, as the basic economic model is structurally unstable.

According to neoclassical economics, any adaptation to climate change can be justified only in terms of increases in some measure of the consumer's wellbeing, such as consumer surplus (CS). Any adaptation to climate change will have a cost. Therefore, at the margin, the optimal amount spent on adapting to climate change will be determined by equating the marginal increase in CS to the marginal costs to the representative consumer. Hence, the adaptation can never be complete, unless it can be achieved at zero cost, which is extremely unlikely. At the margin, the amount spent on adaptation must equal marginal benefits with marginal costs.

Can global climate change be regarded as a marginal change? Nordhaus treats it as marginal only because the large non-marginal change will be spread over a period of 100 to 300 years. When the annual marginal costs and benefits (to the representative US consumer) are spread over hundreds of years *and* discounted, the discounted net stream benefit of reducing GHG reduction appears small. It is therefore not surprising that he concludes that the benefits are also so small that the optimal policy is to reduce GHGs by 13.4 percent by 2075.

2.7: The Social Rate of Discount

There has been a heated intellectual discussion about the proper usage of social discount rates (henceforth referred to as discount rates). Some scholars believe that discount rates should be avoided altogether based on ethical and moral grounds while others think that discount rates should only be used in certain instances with utmost caution. Yet others remain loyal to traditional economic discounting practices. In other words, there is a wide range of positions concerning this issue. Some of these will be described below. First, however, we should define what a "discount rate" is.

The discount rate is used to measure the present value of future costs and benefits. In algebraic terms, $PV = A/(1 + r)^T$, where PV is the present value, A is the future cost or benefit, r is the discount rate, and T is the time period. Jepma and Munasinghe (1998) provide a numerical example of how the magnitude of the discount rates affects the present value term. The present value of US$1,000 will decrease 50 years from now; it is US$608 if a one percent discount rate is used, but only US$87 if a five percent discount rate is used, and a mere US$9 if r is 10 percent! Moreover, longer time frames lead to even more dramatic departures between the different present value terms. In the case of climate change, the costs of adaptation or mitigation occur in the present whereas the benefits of these actions usually occur in the distant future. If the benefits of these options are discounted using high rates, substantial risk reductions 50 or 100 years from now could have little or no present value. Thus it could be decided that it is not worth stopping or limiting the damage of catastrophic events in the future. The use of a discount rate has important ethical implications since the present generation is favoured and future generations are put at a disadvantage by present value calculations conducted in the above manner. To quote Hanley and Spash:

> "In fact, the process of discounting the future, at almost any positive rate, creates insignificant present values for even catastrophic losses in the further future." (Hanley and Spash, 1993, p.135)

The equity and liberty of future generations will be discussed in more detail later in this document.

Jepma and Munasinghe (1998) criticize discounting practices within the framework of welfare economics. According to them, the optimal discount rate can be found when the following conditions are met:

(1) The marginal returns of investment and the rate of interest that borrowing producers are charged are equal.

(2) The marginal rate of consumption is the same as the interest rate acquired by lending consumers.

(3) The conditions of (1) and (2) are satisfied in all places and at all times.

Of course, these conditions seldom hold, which makes the estimation of optimal discount rates very difficult. Jepma and Munasinghe (1998) blame market distortions for this problem. They consequently recommend the use of second best corrections and shadow pricing methods. Given these difficulties one might wonder why discount rates are used at all. Jepma and Munasinghe (1998) provide two major explanations. First, the money invested in public projects could be invested elsewhere instead. The discount rate thus incorporates the opportunity cost (the best alternative forgone), which in turn includes a normal rate of profit. Second, the social rate of time preference (SRTP) specifies that individuals like to consume goods sooner rather than later. The following is a more detailed description of the SRTP.

Jepma and Munasinghe (1998) define the SRTP in algebraic terms. Thus, SRTP = $a + (b.g)$, where a is the pure rate of time preference, b is the elasticity of marginal utility, and g is the growth rate of per capita consumption. The parameter a cannot be estimated in any way, as it is a pure value judgment. It can perhaps be determined through the political process, or determined by some dictator. Next, the parameter b can be estimated for a representative consumer, using some specific functional form of the demand curve, as argued above. But in that case, it could vary widely depending on the functional form of the demand curve. Finally the parameter g, will be highly sensitive to projections about future income growth scenarios. In fact, any estimate of g will itself depend on the discount rate used in the income growth projections, based on investment projects that will be implemented in the future! Thus the exercise is highly circular and any estimate of the SRTP is highly subjective.

Jepma and Munasinghe (1998) also venture temporarily outside of the welfare economics framework, when they indicate that dramatic climate change could severely jeopardize the lives of future generations, in which case investing money into other projects will do them little good. Jepma and Munasinghe question whether compensations can be made over several generations.

Hanley and Spash (1993) are even more critical of the compensation principle, which they find morally objectionable. Their arguments are generally critical of welfare economics. Their critique of standard cost-benefit analysis methods also rests more on a philosophical basis than that of Jepma and Munasinghe. According to Hanley and Spash (1993), the compensation principle is ethically unsound, since it is based on the premise that doing harm can be cancelled out by doing good. The inviolable rights of individuals can thus be transgressed. The compensation principle does not concern itself with questions of equity either, especially when "potential compensation" is actually implied. Nor does it uphold the tenets of democratic government. The compensation principle can lead to the poor getting poorer, and rule of the elite, if that is consistent with the optimal growth path.

The argument of Hanley and Spash (1993) consists of two main strands. First, the compensation principle is defective, since it often refers to a potential for compensation, which is often not realized. Second, even if compensation does take place, it is often calculated according to the wrong criteria. Certain inalienable rights, like the rights of individuals to be free from harm, are not taken into account. Hanley and Spash (1993) provide the following example to illustrate the second point:

There is an unemployed man who is receiving benefits from the state, since he cannot work due to chronic illness. In the beginning his illness and its cause are undiagnosed but eventually it is detected that he has cancer. Moreover, it is proven that the man's cancer was caused by the radioactivity emanating from a public waste dump. According to the compensation principle, the man has already been compensated for the fact that he cannot work as he is in receipt of government payments. This form of compensation is equitable, since he is no worse off in economic terms than he would be otherwise. However, the man is not compensated for his injury. That is, further compensation should be given to him, since his health and his quality of life have been reduced.

Of course, Hanley and Spash (1993) also question whether any amount of compensation can be adequate, given the severity of the injury caused and the man's right to be protected from harm. Many men, women and children will be impacted by how our generation manages our resources. Our predecessors might have been ignorant about the environmental consequences of their actions but we are not. With knowledge comes responsibility. Thus we must ask ourselves: How will we protect the rights of those who come after us? To what extent and in what way should we compensate them for the environmental degradation that we cause?

Hanley and Spash (1993) also discuss the political nature of the discount rate used. They cite the example of when the Nixon administration used high discount rates to help curb government spending. They also mention the practice of adjusting the discount rate based on the political sensitivity of the issue. For instance, public investments in water facilities and irrigation systems are often favoured by a low discount rate, due to their popularity. If the choice of the discount rate is partially motivated by political objectives, this influence should be made explicit. The government should be responsive to public pressure but its actions should also be transparent. The government should not shroud itself in a mantle of objectivity if, in fact, decisions are being made at a different level.

According to Lind and Schuler,

> "…any decision with regard to the mitigation of global warming is more fundamentally a question about equity and the redistribution of welfare from the present and near-term generations to generations in the distant future and from developing countries to less developed ones than it is a typical investment decision that can be analyzed entirely using discounted cash flow methods." (Lind and Schuler, in Nordhaus, 1998, p.60)

Lind and Schuler view economics as a useful tool for analysing the various trade-offs generated by different policies. Moreover they believe that normative questions, that is, questions regarding what should be done, should be resolved through political and ethical analysis. In other words, a public discourse is needed to treat issues properly, such as the optimal amount of mitigation and adaptation needed for climate change. Information on the economic costs and benefits of various options is nonetheless useful. Lind and Schuler also point out that the compensation is difficult to apply over several generations. The social discount rate should not be the same as the private discount rate for the reasons discussed above. Moreover, Lind and Schuler think that questions of intergenerational and intragenerational equity should be analyzed together. The Intergovernmental Panel on Climate Change (IPCC) currently treats these issues separately. Lind and Schuler primarily emphasize equity issues as being of political importance. Their treatment of other values, such as the liberty and the other rights of future generations, is limited.

Sen (1984) provides a critique of discount rates from within the welfare economics framework and he criticizes discounting practices in general. His analysis also examines the technical and the philosophical aspects of discounting the benefits of public investments. The philosophical argument is of particular interest here. Sen distinguishes between the social rate of discount and the private rate of discount. He then states that the former is generally less than the latter. Three arguments support this conclusion. They are as follows:

(1) The super-responsibility argument, which specifies that governments are responsible for protecting the welfare of present and future generations.

(2) The dual-role argument, which argues that individuals have different priorities in the private and the public spheres. Concern about the wellbeing of future generations is more likely to be expressed in the public political forum than in private economic transactions.

(3) The isolation argument, which states that the level of saving for future generations is maximized if a collective effort is made. This argument implies that the members of the present generation will only actively engage in this type of altruistic behaviour when they believe that everyone is contributing in a similar manner.

These arguments are consistent with the framework of welfare economics. As indicated above, they simply advocate the use of a public discount rate, which is lower than the private one. They are not, however, based on any ethical considerations, such as the rights of future generations to enjoy liberty and to be treated equitably. Sen (1984) introduces these concepts in the second part of his paper.

Whether discounting practices are morally acceptable depends on the ethical values that are prioritized. In theory, concerns about the equity of future generations can be accommodated within welfare economics since the winners can, in theory, "compensate" the losers. However, the liberty of future generations cannot be protected within this framework. Equity, measured in economic terms, depends on relative material welfare, whereas liberty is considered an inviolable right independent of economic considerations. In this context, Sen (1984) suggests that it might be unethical for the current generation to compromise the liberty of future generations by irreversibly altering the environment. Moreover, he states,

"The avoidance of oppression of future generations has a value of its own."(Sen, p.195).

Sen then continues,

"Many relevant questions have remained unanalyzed. Are we free to blow natural resources as we like as long as we can justify it on grounds of our low welfare level, high marginal utility, and so forth, as compared with future generations? For example, even if our marginal utility from this resource is greater than that of the future generation, and even if we remain poorer in terms of welfare level than the future generation, can the future generation still legitimately claim that we are grabbing something to which we are not entitled (capitalizing on the arbitrary fact that we could get at the resources before the future generation could)?" (Sen, p.194)

In short, the choice of any particular rate of discount is justified in private sector investments, but in any public sector investment a social rate of discount should be used. For a "small" or marginal project, the use of social or public rate of discounts could be defensible if the sensitivity of the rate of discount is also presented to the decision-maker. Then the decision-maker can assess the extent to which the particular social rates of discount will bias the decision. In the end, some political imperative (for example, providing a hospital, or an MRI for a small rural community) could tip the decision, so that the decision does not rest solely on the choice of particular social rate of discount. In the case of climate change, which is not a marginal "project", it is difficult to see how any particular social rate of discount can be justified.

2.8: An Asset Value Approach to the Environment and Climate Change

In sections 2.1 to 2.7, we have attempted to assess the usefulness of consumption-based valuation as a guide to determining the theory of costs of adaptation to climate change. We argued that the consumption-based approach restricts information only to the utility value of consumption. We also argued that the social choice theory approach of Arrow and Sen is much more "plural" in that it allows for more than utility information. In this section, we review yet another approach to valuation, also inspired in part by Arrow, which we shall call an *asset valuation* approach.

The framework is appealing. Consider the earth, the oceans, the atmosphere and the forests are *natural capital assets*. The interactions of these assets result in *flows* of ecological services that are crucial to sustaining life on earth. For example, the interaction of the oceans, the atmosphere and the forests on land generate a pattern of temperature, precipitation and humidity to which life forms have *adapted* over billions of years. This pattern of interaction is manifested as the *climate*. When climates have changed over geologic time, life forms adapted to the changes, perhaps at a minimal cost. We now face the possibility of accelerated changes in climate and hence the need, by humans at least, of adapting to these rapid changes. What is happening, in the physical sense, is a change in the distributional patterns of climate accompanying a generalized global warming. These changes will impose adaptation costs. If we recognize that the changes are occurring in the flows of ecological services emanating from the natural assets, we can take an asset valuation approach by not just valuing the flows from the point of view of consumption (as in sections 2.1 to 2.7) but by thinking of the assets as a "portfolio" and managing and valuing its "dividends" as an exercise in portfolio choice, or as asset management.

The valuation of environmental assets is difficult because there is no independent metric that associates numerical magnitudes of values to these environmental assets (for example, there is no independent "stock market" to put a value on the individual components of the portfolio of natural assets). The flows of ecological services are perpetuities; they are "dividends" that could flow forever if the portfolio of natural assets is preserved and managed well. If the assets were allowed to be depleted, through neglect or misuse, the depletion or damage could be irreversible.

Moreover, if all the benefits of the flows are unknown, then there is uncertainty associated with the flows. Thus the key concepts here are (a) irreversibility and (b) uncertainty. Irreversibility means that *before* an action is taken there is an "option", but if the action is irreversible, the action kills the option. It is for this reason that economists have expounded the idea of an environmental option value (EOV). The defining characteristic of EOV is the extra benefit that arises in the future as a result of preservation or conservation of the natural asset.

The literature distinguishes between an option value (OV) and quasi-option value (QOV). OV depends upon risk aversion and results from the individual's uncertainty about the flows of ecological services in the future when depletion of the assets is irreversible. QOV, on the other hand, is independent of risk aversion and depends upon the prospect of learning and receiving more information about the consequences of irreversible damage or depletion. Both OV and QOV assume rational behaviour under risk, but do not cover cases where events are unanticipated or where the probability of events is imprecise. When the number of events is exhaustively known, then the probability of each event is also known. This is called soft uncertainty. However, OV and QOV do not apply to unanticipated events, such as the emergence of the ozone hole or the occurrence of the virus *Ebola* or BSE (bovine spongiform encephalopathy). Such unanticipated events are characterized by hard uncertainty. Hence the probability of occurrence is unknown.

Corresponding to soft uncertainty and hard uncertainty, both OV and QOV should be considered. Hence there are four relevant concepts, OV under soft uncertainty, OV under hard uncertainty, QOV under soft uncertainty and QOV under hard uncertainty.

2.8.1: Option Value under Soft Uncertainty

Option value is based on the assumption that a decision-maker has a preference for intertemporal flexibility. Intertemporal flexibility assumes that:

> "Good current actions may be those that permit good later responses to later observations" (Marschak and Nelson, 1962, p.42).

This permits a decision-maker to take advantage of information that comes later in time. Thus option value is the *extra* component of benefit associated with the conservation of a natural asset but an option value is positive only if there is uncertainty. Under certain conditions, OV can be shown to be positive. Thus an ecological service has an additional component of value that should be taken into account. This is of course not reflected in market prices because in general there are no market prices for ecological services.

2.8.2: Quasi-option Value under Soft Uncertainty

QOV identifies an extra value to the preservation of an option in order to take into account irreversibility and new learning. A typical example of QOV is biodiversity; for many tropical plants, marketable consumption values are not yet known, but could be revealed later through research. Under certain conditions, QOV can be shown to be positive. The possibility of new learning suggests that there is value to preserving future options.

2.8.3: Option Value under Hard Uncertainty

Hard uncertainty exists when the probability of events is not exhaustively known or when the probabilities of occurrence are non-additive. With the appropriate expected utility model, it can be shown that there is a premium associated with hard uncertainty. Therefore, OV under hard uncertainty provides a rational policy towards preserving environmental assets when their use or exploitation might lead to catastrophic changes.

2.8.4: Quasi-option Value under Hard Uncertainty

Arrow and Fisher (1974) show that if there is uncertainty, even though there is no assumption of risk aversion, something like a "feel of risk aversion" emerges when decisions are irreversible. Quasi-option value under hard uncertainty is therefore completely independent of risk aversion. Henry (1974a, 1974b) shows that the concept of quasi-option value is the gain from retaining the option to make both irreversible and reversible actions in the future and its sign is always positive. This positive premium arises from the asymmetry between reversible and irreversible actions and the independent learning process. It is always costly to kill an option for the future.

2.8.5: Lessons from Option Values

The literature on option values thus demonstrates an extra value of environmental assets by attaching an additional premium to the value of ecological services flowing from them. Therefore, option values are more important for a policy of mitigation for climate change rather than adaptation. However, the adaptation process will be more costly when there is damage to environmental assets, which inhibits the flow of ecological services. There is a cost to adapting to climate change because we have initially adapted to a specific set of environmental conditions and flow of ecological services. When the flow of ecological services changes and environmental conditions change as a result of alteration in climate, humans are forced to adapt. In addition to the cost of adaptation induced by these climatic changes, there is an additional cost associated with the loss of options. Some options for adaptation will be eliminated in the process. Therefore, the concept of option values draws attention to these additional costs, which would otherwise be ignored.

Option values therefore further complicate the optimal adaptation response. Climate change will occur over a long time period, say over the next 200 years. For short-lived assets, the optimal adaptive response may be fairly continuous (for example, changing codes for antennae every 20 years) but for long-life assets (such as international bridges), the optimal adaptive response may require “over-dimensioning” now. This rules out the option of adapting to later information. Not strengthening an international bridge now, however, may involve catastrophic losses in the near future due to an extreme weather event that weakened the international bridge. If we adopt the precautionary principle, then the adaptive response must be taken now even if it kills an option later, such as adapting to different kind of a bridge later in the light of new information. All this is saying is that the importance of the precautionary principle is primary (that is, we wish to avoid catastrophic accidents due to a major bridge collapsing), whereas costs incurred in over-dimensioning the bridge are "a lesser evil". That is, the option of a safer bridge now is valued more than a technologically better and cheaper bridge built later.

The literature on option values acknowledges that we have a “portfolio” of natural assets, which yield “perpetual dividends” in the form of ecological services. In the case of climate change, there will be a change in the *distribution* of some of these services (such as the hydrologic cycle and the carbon cycle), which will involve costly adaptation measures. If these adaptations are seen as portfolio management actions, designed to preserve the natural capital assets and their perpetual dividends, then the key guiding principle should be the preservation of capital. An example would help: consider the law of trusteeship and the obligations that the law imposes on an executor of an estate. The moral and legal responsibility of an executor of an estate or a trustee is always to preserve the capital that will be passed on to the beneficiaries of the estate.

In the environment, the preservation of capital requires adaptations that are not determined by the MB = MC rule, but by the need to *restore* the capacity and capability of the biosphere to continue to deliver the ecological services. This requires the preservation of ecosystem integrity as part of an adaptation strategy. Thus part of an adaptation strategy would be to preserve *future options* by preserving the portfolio of natural assets, so that the same "ecological" dividends continue to follow in the future. This must be done under conditions of hard uncertainty, as the probabilities of events associated with climate change are not known. Capital preservation requires an approach that is not governed by comparing the marginal costs and benefits of adaptation to climate change. One approach to capital preservation is *restituto in integrum.*

2.9: General Conclusions

We have shown that most calculations of the sort carried out by Costanza or Nordhaus are really thought experiments, with specific and arbitrary functional forms. Varying the functional forms or the parameters used in a variety of demand functions does not lead to convergent, error reducing estimates of consumption benefits. The reason for this non-convergence is that the basic economic model is not structurally stable. When scientists encounter models that are not structurally stable, they abandon them and search for better models that represent reality. Economics and ecological economics do not have empirical and scientific criteria for model verification and validation. To be content with thought experiments based on a single dimension of money is not enough, and exclusive reliance on these thought experiments is grossly misleading.

We conclude that a unidimensional metric of consumer surplus measured in dollar terms can only trivialize the problem of policy towards global climate change. The consumption-based valuation is at the heart of the MB = MC rule. In this rule, MB is determined by consumption-based valuation, which as a matter of logic must be based on *declining* marginal benefits (to adaptation or mitigation). In the case of climate change, it *cannot* be assumed that marginal benefits to adaptation measures must be declining. Indeed, if the costs avoided are the benefits, then these benefits could well be rising. On the other hand, the marginal costs of adaptation measures to be undertaken must also be rising, as the pace of climate change accelerates. Therefore, with marginal costs and marginal benefits both increasing, there is a possibility of no intersection and no equilibrium (Figure 2) or of multiple equilibria (Figure 3) if the curves are nonlinear.

Figure 2: Marginal Costs and Marginal Benefits under Conditions of No Equilibrium

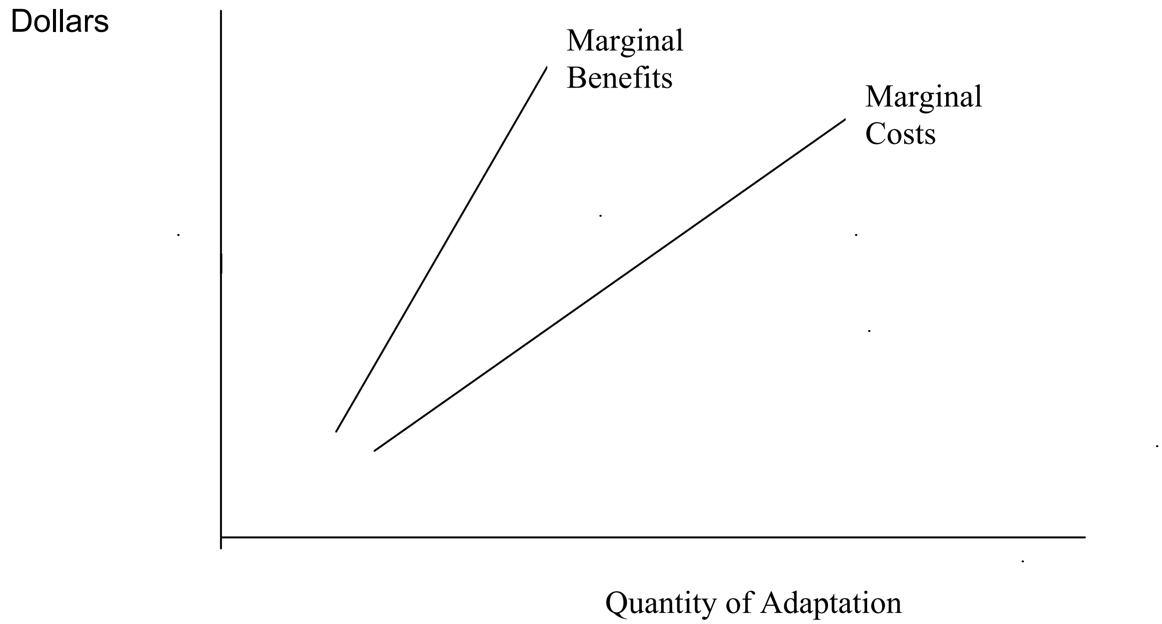
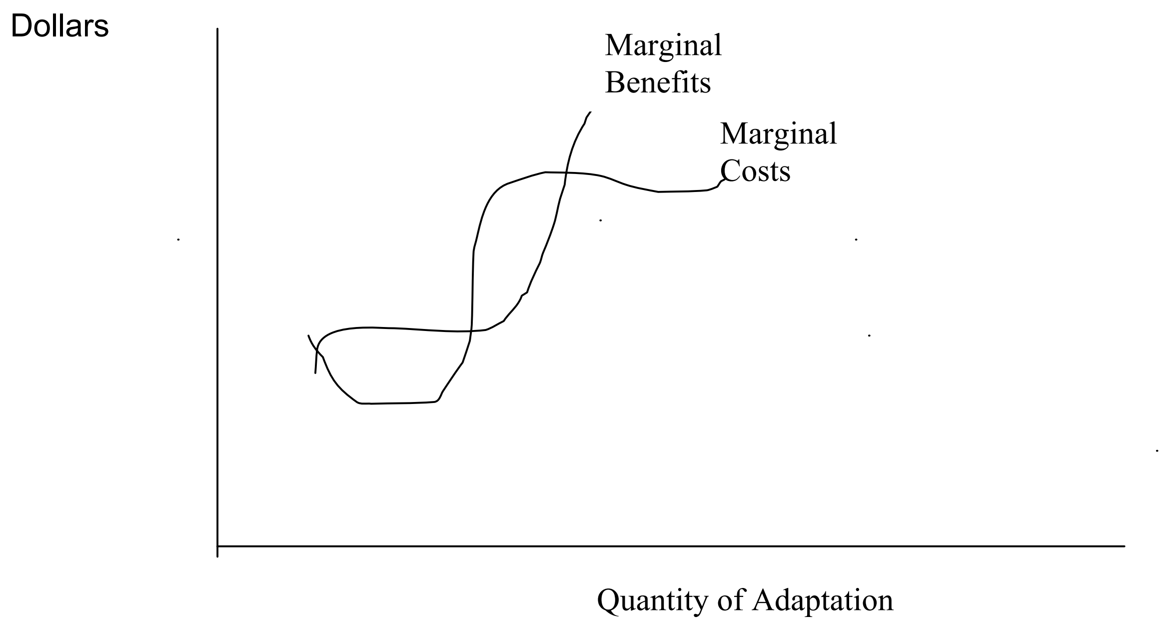


Figure 3: Marginal Costs and Marginal Benefits under Conditions of Multiple Equilibria



We conclude that, for the variety of reasons given in sections 2.1 to 2.8, the MB = MC rule is not appropriate for evaluating adaptation to climate change. We argue that the new development in environment option values (also pioneered by Kenneth Arrow and others) offers a new and refreshing approach to adaptation to climate change. This approach views the biosphere as a portfolio of natural assets that yield perpetual dividends in the form of ecological services. Therefore, adaptation to climate change is a portfolio management action designed to preserve the capital assets and their perpetual dividends, where climate change is a change in the distribution of these dividends which can threaten the integrity of the portfolio of assets.

It follows that the key guiding principle should be the preservation of capital, which cannot be guaranteed by the rule that expenditures on adaptation should equate marginal costs with marginal benefits. The preservation of capital also requires *restoring* the capacity and capability of the biosphere to deliver the ecological services. Consequently, preserving ecosystem integrity must be part of an adaptation strategy.

UNEP (1998) correctly distinguishes *economic opportunity costs*, which, if taken seriously, indicates what is at stake here. The classical concept of economic opportunity costs defines what society would *lose*, if the natural assets were damaged or destroyed. The quantity of adaptation cannot be determined by smooth, linearly additive marginal cost and marginal benefit curves. In the real world, adaptation costs would be “lumpy” and so nonlinear. The literature on option values shows that, in some cases, adaptation may require overdimensioning in order to take into account nonlinearities.

The preservation of capital is an "investment approach", whereas the MB = MC rule is based on a "consumption-based approach," and in the latter, the declining marginal benefits are assumed to be similar to consuming any other goods. For consumer goods, it is reasonable to assume that the marginal utility of consuming *more* of a particular consumer good declines. When expenditure on adaptation is form of investment, it cannot be assumed that the marginal utility of ecological services or of the human-made capital will be declining with increased adaptation.

The consumption based approach limits information to utility of consumption in the valuation of benefits. A more plural approach is to admit more information in the formulation of the model. An example of such an approach is the social choice theory approach, which was also pioneered by Arrow. A full treatment of this approach is outside the scope of this report, but an introduction on how the results in the theory of social choice can be used for public policy is provided in Dore and Mount (1999) and an examination of the subject is also found in Arrow and Raynaud (1986).

In short, we are arguing that adaptation expenditures will be in the form of an investment, and investment should be valued for the stream of benefits that it will generate. Taken together, the adaptation expenditures will be aimed at preserving capital (both natural and human-made). Therefore adaptation costs are "portfolio choice" decisions, designed to maintain the integrity of natural and human-made capital.

Part 3: Empirical Estimates of Adaptation Costs

Having discussed adaptation costs from a theoretical perspective, we now examine practical attempts that have been made to estimate these costs numerically. We begin by looking at estimates for Canada and then turn our attention to existing estimates done at the sectoral level. We then make some observations on recent estimates from the UK. A number of these sectoral studies have already been discussed from a more theoretical standpoint in Part One.

3.1: Existing Estimates of the Costs of Impacts and Adaptation in Canada

There is no sound basis for estimating the costs and benefits of adaptation and residual impacts to climate change in Canada. Some progress has been made in identifying adaptation options in response to climate change, but there is little information on the actual costs and benefits of adaptation, or the residual costs that occur despite adaptive measures.

A wide range of adaptive options to climate variability and climate change in Canada, from responses to past and present climate conditions and possible future climate scenarios, has been compiled in Smit (1993). Costs and benefits of adaptation options are not included and the task of estimating them across many sectors and geographical areas is daunting. Other methods must be sought in order to develop reasonable estimates of adaptation and residual costs and benefits. Before doing so, however, it is worth noting that there is considerable agreement in the literature on at least three key issues:

- The costs and benefits of adaptations vary geographically and from economic sector to sector. Further research is needed to improve our understanding of these differences.
- Many measures that have been promoted for adapting to climate change are small steps up from currently available technologies, suggesting that associated costs could be small, if initiated early.
- Canadian decision-makers may have a good, albeit imperfect, understanding of the broad range of adaptation options available for current climate. It is uncertain if this knowledge is sufficient to enable successful adaptation to climate change by decision-makers in the future.

One study (Herbert and Burton, 1994) has attempted to estimate the costs of adaptation to current climate in Canada. The results are useful but need improvement. Other studies have estimated the possible costs of adaptation to, and residual impacts of, climate change. They are based on modification of rather crude estimates originally made for the US and their value is therefore limited.

In the Canadian context, Herbert and Burton (1994) estimated current costs of adaptation to present climate at over CAN$11.6 billion (Table 1). The results are by no means rigorous. The survey results include total expenditures in eight major sectors, percentage and cost attributable to climate adaptation, and possible trends under climate change. The costs of energy are subsumed under the appropriate sectors, while some adaptive costs were ignored (health care adaptations, for example). Sectoral costs attributed to climate are based on:

- Published material such as air transportation costs of aircraft de-icing, runway snow and ice removal and aviation weather services
- Expert opinion on current expenditures at the national level (an estimate of four percent of construction costs attributable to climate elements)

Table 1: Estimates of the Cost of Adaptation to Current Climate in Canada and Possible Trends under Climate Change

Sector/Activity	Total Cost (CAN$ million)	% Attributable to Climate Adaptation	Cost of Climate Adaptation (CAN$ million)	Possible Trend
Transport	7,368		1,657	Decrease
Air	83.5	100	83.5	Decrease
Marine	258.8	55	143.8	Decrease
Rail	702.0	29	203.2	Uncertain
Roads	6,323	19	1,227	Decrease
Construction	50,000	4	2,000	Increase
Agriculture	1,887	70	1,330	Increase
Forestry	556	72	403	Increase
Water	1,058	73	767	Increase
Flood Control	4.7	80	3.8	
Household Expenditure	6,023	88	5,296	Decrease
Emergency Planning	14.4	75	10.8	Increase

Weather Information	189	100	189	Increase
TOTAL	**19,096**	**61**	**11,653**	
Source: adapted from Herbert and Burton (1994). Values are based on 1991 or 1992 dollars.				

It is difficult to assess how adaptation costs to the current climate will change under future climate conditions, but reasonable estimates of trends for specific sectors can be made. Possible trends in Table 1 are judged for Canada from climate change literature of the early 1990s. Adaptation costs in agriculture, forestry, water, emergency planning and weather information are expected to increase, while those associated with transportation and most notably household expenditure are expected to decrease. This is just a guess, which could turn out to be wrong; it is quite possible that the impact of climate on water supply could severely raise costs of water infrastructure.

Residual costs remaining in spite of adaptation are variable and not well defined. Between 1984 and 1994, the Canadian insurance industry paid more than CAN$1 billion to compensate losses sustained through major natural disasters. This figure is rising (Brun, 1997). Some of these costs would be due to maladaptation and some due to extreme weather events. The claims arose from thunderstorms, tornadoes, hail, windstorms and flooding, and concerned damage to homes, businesses and vehicles. The total costs to Canada, including the uninsured costs and damage to public property, are estimated at more than double the insurance costs. This figure does not include smaller events, suggesting that the true residual costs are much higher.

Prior to the Red River flood of 1997 and the ice storm of 1998, the costliest single Canadian weather event during this decade was the Calgary hailstorm of 1991. It caused CAN$450 million in economic losses, with CAN$360 million sustained by the insurance industry. In July 1996, there were CAN$295 million insured costs for severe hailstorm damage in Calgary and Winnipeg. Excessive precipitation and flooding in the Saguenay region in July

1996 caused estimated damage of CAN$1 to CAN$1.5 billion, of which only CAN$350 to CAN$400 million was insured. At the other climatic extreme, extensive drought throughout the Prairies in 1988 resulted in CAN$1.4 billion in insurance payments and government subsidies. These are only a few, albeit severe, examples of the residual costs associated with extreme events and it is quite possible that such costs will increase under climate change.

While these figures may suggest that Canadians are not adequately prepared to deal with extreme events resulting in major disasters, the recent Red River flood offers useful insights. The costs of the flood are extensive, but they could have been much higher if it were not for a CAN$50 million floodway around Winnipeg constructed between 1963 and 1967, and the rapid construction of the 40 kilometre long Brunkild Dike. The floodway has paid itself off many times over by protecting the city of Winnipeg from no less than three major floods. Despite the heroic efforts of many volunteers and the extensive building of protective infrastructure, the costs associated with the most recent flood are still large. More drastic measures, if land use and/or the location of human activities are not changed, may be necessary. Adaptive responses may also be required in other regions vulnerable to climate change and rising sea levels. An upgrading of existing dikes to protect the lower Fraser valley in British Columbia may be necessary and will cost hundreds of millions of dollars.

Careful and proactive planning, especially in infrastructure with a relatively long life, is cost effective and sensible. Planners in the town of Milton have recommended spending an additional CAN$7 to CAN$10 million on waterworks to accommodate expected water shortages under climate change. This amount represents an extra 10 to 15 percent of the base cost, yet is much cheaper than if changes were instituted later. The design of the recently completed Northumberland Strait Bridge included an allowance for a one metre potential sea level rise due to global warming over the 100 year life of the structure. The added cost of increasing the height of the bridge was small relative to both the total project cost and the possible future costs of countering the effects of a sea level rise.

Tol (1995) considered the implications of climate change in the US and Canada under an equilibrium 2.5 degree Celsius warming and a 50 centimetre rise in sea level due to doubling of atmospheric concentration of CO_2. By scaling up estimates of 1.5 percent reduction of North American GDP in 1988, Rothman, *et al.*(in Environment Canada, Vol.VIII, 1998) estimated that climate change would entail losses of CAN$8.3 billion (1986) in Canada (Table 2) based on a doubling of CO_2. Human mortality and morbidity make up nearly half of the total damages. Tol (1995) used a value for a statistical life of about US$3.5 million, and neglected impacts on forestry, energy, water, air and water pollution and many other potential impacts. Only coastal protection is clearly an adaptive measure among Tol's categories. Dryland loss, wetland loss and the impact on agriculture reflect costs of adaptation plus residual damages.

These estimates are extremely crude and shrouded in a wide, yet unknown, band of uncertainty. They are based on heroic assumptions and depend on a constantly evolving understanding of the impacts of climate change and the economic values. A year later, Tol (1996a) substantially revised both the total cost and the distribution among sectors for North America, showing US$55.2 billion total instead of the former estimate of US$74.5 billion. In this later study he quadrupled the loss of species, whereas the estimate of mortality losses was dropped by nearly 75 percent.

Table 2: Estimates of the Cost of Doubled CO_2 for Canada in 1988
(2.5 degree Celsius, 50 centimetre sea level rise)

	Data for N. America (Tol 1995)		**Calculated Costs for Canada**
Category	**US$ Billion**	**% Total**	**CAN$ Billion 1986**
Coastal Defence	1.5	2.0	0.167
Dryland Loss	2.0	2.7	0.223
Wetland Loss	5.0	6.7	0.557
Species Loss	5.0	6.7	0.557
Agriculture	10.0	13.4	1.113
Human Amenity	12.0	16.1	1.336
Human Life	37.7	50.6	4.197
Migration	1.0	1.3	0.111
Natural Hazards	0.3	0.4	0.033
TOTAL	**74.5**	**100%**	**8.294**
% of GDP	**1.5**		

Source: Rothman, *et al.* (in Environment Canada, 1998).
Data for Canada assumes sector share as in the US, total Canadian GDP from CANSIM.
Several categories, such as coastal defence, dryland and wetland loss, and agriculture, reflect costs of adaptation plus residual damages.
Neglected:

- impacts on insurance, construction, transport, and energy supply,
- damage from non-tropical storms, river floods, hot/cold spells, and other catastrophes,
- other ecosystem losses,
- morbidity, physical comfort, political stability, hardship, and other human impacts.

Categories considered in other studies, but not considered by Tol: forestry, energy, water, other sectors, air pollution, water pollution.
A statistical life, the "personal willingness to pay for risk reductions" (Pearce, 1997, p.3), is assessed at $250,000 plus 175 times per capita income (Tol 1996b).
Migration is the cost of incorporating immigrants into the social welfare system (Pearce, *et al.*. 1996).

Using the newest information about impacts on selected sectors, Tol (1999a) produced estimates for North America for one degree Celsius warming and 20 centimetre sea level rise. It is unclear how assumptions about warming that increased to 2.5 degree Celsius and a sea level rise to 50 centimetres would affect the new estimate. Tol scaled his 1995 results for 2.5 degree Celsius warming and 50 centimetre rise proportionately by a factor of 2.5 to make a comparison possible with the newest estimate. From a total loss of US$30 billion, the estimate rose to a welfare gain of US$175 billion (3.4 percent of North American GDP). Tol (1999a) somewhat arbitrarily ascribed a standard deviation of US$107 billion to the total estimate. He accounted for gains in agriculture (due to a 2.5 degree Celsius warming), forestry and nature (ecosystems, species and landscapes) and losses due to sea level rise (loss and change in value of wetlands and drylands, protection costs, and population migration), mortality (from malaria, schistosomiasis, dengue fever, heat and cold stress, and cardiovascular afflictions), increased energy demand and water resource changes. Impacts on agriculture with adaptation amount to a net gain in welfare, compared to the considerable loss estimated by Tol (1995) and Tol (1996a). Human amenity, recreation, tourism, fisheries, construction, transport, energy supply, morbidity and many other impacts were omitted because no comprehensive, quantified impact studies have been reported.

Using the static model of Tol (1999a) as a starting point, a dynamic model of Tol (1999b) attempts to take into account sectoral responses to climate change and the changes in society's vulnerability (sensitivity modified by adaptation) for the years 2000 to 2200. The model is beset with more uncertainties and heroic assumptions but gives some insights. In the short term, the estimated sensitivity of a sector to climate change is the crucial parameter. As time progresses, the change in the vulnerability of the sector is often increasingly important when estimating the magnitude of the total impacts. For North America, total impacts are negative in the beginning (losses of up to 1.5 percent of GDP by about 2040). This reverses very sharply thereafter, reaching a GDP gain of three percent in the middle of next century, which then gradually diminishes, reaching constant GDP losses of below one percent beginning in 2140. In the poorer regions of the world, the negative impacts tend to dominate.

The static and the dynamic models are not compatible. The sharp change in sign of impacts after 2040 is indicative of some deficiencies in the dynamic model. The static gain of 3.4 percent of GDP “matches” the peak three percent dynamic gain about 2050, but the coincidence may be spurious. Both estimates may be of the wrong sign and wrong order of magnitude since natural resource valuation is rather inadequate.

Mendelsohn, *et al.* have developed predictive equations that are based on a series of studies in the US, excluding the tourism sector (Mendelsohn and Neumann, 1999). The equations relate market value to average temperature and precipitation levels, atmospheric concentrations of CO_2, length of coastline, land area and other variables. The sectors considered are agriculture, forestry, coastal resources, energy, water and tourism. The impacts of a changed climate are calculated for each sector by varying the climatic parameters. The portion of Canada north of 65° latitude (well over half the land area of the three territories of Canada) was omitted on the assumption that economic activities are limited there.

Some authors believe that the equations provide helpful estimates of aggregates for Canada, if not for the specific sectoral impacts, costs and benefits (Kloeppel, 1997; Mendelsohn, *et al.,* 2000). For Canada, a warming of 2.5 degrees Celsius in 2060 is estimated to provide significant overall positive benefits, based largely on gains in agriculture and forestry. A closer examination of the studies raises a number of questions about:

- The adequacy of representation of the dynamics of adaptive capacity and vulnerability of sectors in the equations
- Optimistic assumptions about the benefits to agriculture and forestry from CO_2 fertilization

- The lack of consideration of many of the costs of adaptation
- Restriction to direct-use value and only a subset of economic sectors, and the exclusion of indirect and non-use values of natural resources
- The adequacy of impact estimates using single, country-wide, annual average values for temperature and precipitation
- The application of these results to countries with climatic, biological, and socio-economic system characteristics outside the range over which the equations were estimated.

3.2: Sectoral Adaptation Costs

While the above studies generate cost estimates for various sectors, they utilize a top-down approach. In this section, we critically review attempts that have been made specifically to estimate sectoral climate change adaptation costs. This section is organized as follows:

- Section 3.2.1 is a discussion of the costs of adaptive responses for coastal protection.
- Section 3.2.2 is an examination of adaptation cost estimates in the area of public infrastructure.
- Section 3.2.3 is an examination of adaptation cost estimates in the area of the energy sector.
- Section 3.2.4 is a review of several cases from the literature on the economic impact of climate change in the agriculture sector, in which adaptive response cost is treated as an important component.
- Section 3.2.5 is a review of the economic impact of climate change on forestry.
- Section 3.2.6 is a summary of section 3.2.

3.2.1: Coastal Protection

Estimates of the cost of adapting to climate change are seldom measured by thoroughly examining individual sectors of interest. However, cost assessments of coastal protection under various accelerated sea level rise (SLR) scenarios are sometimes conducted by maintaining a sector specific focus. Several costing exercises will be critically reviewed to evaluate the various methods used to establish the costs and the optimal costs of coastal protection.

In "Valuing Climate Change: The Economics of the Greenhouse", Fankhauser (1995) conducts a cost-benefit analysis to establish the optimal degree of coastal protection in the OECD countries. He finds that coastal protection should cover 50 to 80 percent of coasts and open beaches, if the best response path is followed. The optimal level varies according to the different sea level rise (SLR) scenarios. Wealthy, densely populated countries, and areas of high economic value such as harbours and cities, are more highly protected than are others (Fankhauser, 1995).

In Fankhauser's model, the basic objective is to minimize the costs associated with the rising sea level over time. The cost elements he isolates are protection costs, dry land loss and wetland loss. His model also incorporates three response options (as defined by the IPCC). Communities are expected to either (1) retreat from currently developed areas, (2) accommodate to the new environment, or (3) protect areas by providing beach nourishment or constructing dikes. He estimates the optimal levels of coastal protection for OECD countries for different SLR scenarios by using the ratio of costs under full protection to the costs under full retreat. Both the costs and the benefits of coastal protection rise with higher sea levels since more land is at risk and more costly construction is needed. The relative magnitude of these two phenomena helps determine whether additional protection measures should be financed or not.

According to Fankhauser, the optimal protection level in Canada is below 50 percent.

This implies that only 50 percent of the vulnerable areas should be protected (Fankhauser, 1995). The total cost of adaptation is estimated at US$6.92 billion (in present value terms, 1990-2100) based on a 26 percent protection rate of Canada's open coasts and a 40 percent protection rate of Canadian beaches. The base year and discount rate of this dollar figure is not given, making it difficult to compare to other estimates.

Fankhauser (1995) noted that poorer nations, such as Turkey, and sparsely populated countries, such as Canada and Australia, tend to have lower protection levels as a result of lower land values. This result is not surprising as GDP and population levels were used to estimate the value of land in the first place. If the market value of land were used, a different conclusion might have been obtained. In other words, the results are highly sensitive to the initial assumptions that are made. The relocation costs of people are not taken into consideration nor are any non-market goods, other than wetlands, accounted for in this cost assessment. Fankhauser also assumes that coastal protection is to be built as it is required. In other words, the timing of defensive measures is not taken into account. This may be a major omission as the costs of adaptation often depend on the timing. Insightful, long-term planning has been found to reduce much higher costs in the future. Of course, Fankhauser may have minimized the value of this effect, as he assumes no surprises (the sea level is expected to rise gradually, with perfect knowledge). He also relies on geographic data with a coarse resolution for his analysis.

In contrast, Yohe, *et al.* (in Mendelsohn and Neumann, 1999) take geographical detail into consideration in their estimation of the optimal protection costs of sea level rise in the US. They base their estimate on inundation profiles using computer-based maps, which consist of 500 metre square partitions. This sophisticated technology provides a better measure of the land expected to be inundated. Moreover, it measures the effects of different SLR scenarios over time, allowing the authors to construct a cost-benefit analysis based on increments by decades. Their objective is to isolate the optimal response to rising sea levels by maximizing welfare, that is, the net benefits of protection minus the net costs, at different points on the time horizon. The methodology of Yohe, *et al.* is similar to that used by Fankhauser in some respects. In both studies, a cost-benefit analysis is used to estimate the optimal level of coastal protection, which in turn determines the magnitude of adaptation costs, if the optimal path is taken. The costs and the benefits consist of the same components, that is, the value of the land potentially lost and the cost incurred by carrying out the protection measures.

Given the time element in the study conducted by Yohe, *et al.*, the value of land is measured at the time of inundation. This figure is projected by taking into account population growth and growth in real income. As onshore property will be replaced by previous inland property, the value of inundated land is estimated to be the equivalent of the latter. Yohe, *et al.* also estimate the value of the coastal structures. However, the market value of the structures is expected to depreciate as they become threatened. According to this model, only fast, unanticipated destruction would leave structures with a market value that does not tend toward zero. Such surprises are not incorporated into the estimates of Yohe, *et al.*

More importantly, no attention is paid to the fact that the structures in question would have a market value if protection measures were put into place. Excluding this possibility, and assuming that market agents will also expect complete inundation in the near future, grossly underestimates the market value of coastal structures. As the decision to build coastal protection is contingent on the value of property protection, this model becomes a self-fulfilling prophecy. According to Yohe, *et al.*, the estimates of land value are useful for evaluating (1) potential benefit of protection and (2) the potential costs of abandonment, and/or the cost of protection. In other words, evaluating coastal structures in the above manner reduces both the benefits of protection and the costs of abandonment or protection.

The costs of protection, on the other hand, consist of fixed and variable costs. Yohe, *et al.* establish these costs based on a review of published literature. The fixed costs of dikes/levees are assumed to be US$500 to US$2,600 per metre (base year 1990), and sea wall and bulkhead are US$500 to US$13,200 per metre (base year 1990). The baseline results for both categories are US$2,500 per metre (base year 1990). Maintenance costs are four and 10 percent for soft and hard structures respectively. The magnitude of fixed and variable costs vary depending on the SLR scenario.

As mentioned earlier, the total costs of adaptation are based on the costs of the optimal level of protection and the cost of abandoned property. The present value of these costs is between US$100 and US$200 million per year for the US, using a three percent discount rate. These estimates are obtained by aggregating data from all the coastal areas. They are lower than previous US estimates, since the precision of the computer-mapping method allows abrupt contours that protect property to be taken into account. The manner in which the market value of the land and structures is determined also reduces the magnitude of cost estimates.

The measurement technique used to assess the area of vulnerable coasts is superior to the one used by Fankhauser (1995) since it provides more detail. However, the estimation of land value is not soundly based. A detailed analysis of the actual dynamics of the specific land markets in question would provide a better estimate of the value of vulnerable land.

Zeidlar (1997) estimates the market value of land in Poland by projecting future socio-economic developments such as the expected population growth in coastal communities, a transition from agriculture to tourism, and a growth in infrastructure and the service sector.

Since Poland has a transitional economy, he also expects the market dynamics in 2025 to approximate those of Holland. The future costs of coastal protection are similarly expected to approach the current Dutch values.

Zeidlar's study includes the SLR scenarios (0.3 and one metre by 2100, and 0.1 and 0.3 metres by 2030) under three adaptation strategies (full protection, limited protection and retreat). Historical flooding patterns, wind direction and speed are also incorporated into his model. The analysis of the optimal level of protection differentiates between the particular vulnerability profiles of four different areas of Poland. Thus, Zeidlar compares the costs and the benefits of adopting the various adaptation strategies based on different SLR scenarios for each area.

In the SLR scenario of one metre by 2100, the cost of full protection for all areas is estimated to be US$6 billion (base year 1992) compared to the value of the vulnerable land, which is approximately US$30 billion (base year 1992). In open sea segments, full protection would constitute 16.3 kilometres of dikes, 21.7 kilometres of sea walls and one kilometre of offshore breakwaters. The relative costs and benefits of the most severe SLR scenario justify the adoption of these protection measures when the high level of risk is taken into account. The potential damage caused by the more moderate SLR scenarios does not approximate the costs of providing full protection in one of the four areas. Moreover, the value of adopting limited protection is only justified in these scenarios if the high value at risk is taken into account. Zeidlar describes his study as a very coarse cost-benefit analysis and he admits to the high level of uncertainty involved in generating the estimates of costs and benefits. Zeidlar uses similar methods to those adopted by Yohe, *et al*.(in Mendelsohn and Neumann, 1999) and Fankhauser (1995) inasmuch as he evaluates the costs of optimal protection based on a cost-benefit analysis. Poland's particular position as an economy in transition does, however, necessitate a projection of economic development, which is different from simply assuming a certain level of growth in GDP. In other words, Poland has to deal with a higher level of uncertainty than Canada and the US in terms of economic development or climate change. Nevertheless, the Canadian and American economies may also experience structural shifts similar to those included in Zeidlar's model. They consequently should be included in North American estimates, if this can be done without detracting from the simplicity and reliability of the model.

Nicholls and Leatherman (in Strzepek and Smith, 1995) examine the impact and adaptation costs of accelerated SLR for Argentina, Nigeria, Senegal, Uruguay and Venezuela. For each country, they assess the level of vulnerability, the per unit cost of beach nourishment, sea walls and harbour upgrades, and the appropriate mix of coastal defence measures depending on the response option chosen. In other words, their study attempts to establish the specific protection needs of the particular nation in question. For example, extensive beach nourishment is expected in countries with a large area of tourist beaches. In Uruguay, nourishing beaches accounts for 98 percent of the protection costs.

<u>Aerial videotape assisted vulnerability analysis</u> (AVVA) is used to assess the coastal characteristics and supplement the limited amount of domestic data available for these countries. A vulnerability profile is consequently established for the SLR scenarios of 0.5 and 1.0 metres by the year 2100. The magnitude and impacts of land loss, and potential response options are estimated for these two scenarios. According to Nicholls and Leatherman, countries will respond to accelerated SLR by providing <u>no protection</u> (NP), <u>important areas protection</u> (IAP) or <u>total protection</u> (TP) for their coasts.

As mentioned earlier, the costs of coastal protection vary depending on which response is chosen. The magnitude of the sea rise is also positively correlated with total costs. In this study, the highest costs are associated with Uruguay. These costs are estimated at US$2070 to US$2142 million for IAP and US$2155 to US$2729 million for TP for the 0.5 metre SLR scenario, and US$2905 to US$2995 million for IAP and US$3126 to US$3793 million for TP for the one metre SLR scenario. About six percent of gross investment (the money available for investment) in Uruguay currently consists of coastal protection costs. This percentage is expected to increase under accelerated SLR scenarios unless economic development offsets this effect. Nicholls and Leatherman do not assess the affordability of the various response options since they believe that the economies in question may develop at a sufficient rate to absorb these costs.

Yang (in Smith, *et al.,* 1996) does not use the cost-benefit analysis approach to estimate the optimal level of coastal protection. Nor does he investigate different SLR scenarios when formulating an adaptation strategy for the Pearl River delta. He simply assumes that the sea level will rise by 40 to 60 centimetres before 2060, and that given the vulnerability and the high economic value of the area, a wide range of adaptation measures should be adopted. The measures to accommodate climate change include:

(1) Strengthening and reconstructing dikes and sea walls

(2) Raising the design standards

(3) Preventing flood and surge disasters

(4) Monitoring networks

(5) Transforming agriculture and husbandry to aquaculture

(6) Adopting "soft" structural measures such as advancing science and educating the public.

The cost of implementing these measures is 0.12 percent of local GDP, whereas the economic losses that the area may suffer without these measures will represent 54 percent of the local GDP annually.

Despite apparent differences, the costing exercises above have many of the same limitations. They do not take into account:

- Relocation costs
- Adaptation costs associated with "surprises"
- The cost of friction between vulnerable and non-vulnerable areas
- The value of the land for those who do not wish to sell at the market rate
- The rights of individuals to remain unharmed, and the professed role of the state to protect them

Moreover, the cost-benefit analysis conducted ignores:

- Costs of human suffering
- Costs of environmental degradation
- The value of human and other vulnerable life forms
- The value of ecological services

Comprehensive estimates of the cost and benefits of adaptation should ultimately include all of the above variables. Until that is technically feasible, a qualitative analysis of the magnitude of costs and benefits that are translated into monetary terms with difficulty should complement the quantitative analysis of more easily measured variables. Nevertheless, some technical solutions are available in the short term. For the evaluation of land, the willingness to accept loss rather the willingness to pay may be the more appropriate measure of value. A rights-based approach rather than a utilitarian approach can be used to capture various other non-market values such as the rights of individuals to be protected from harm. Some non-market costs and benefits are already being assessed. For instance, in Indonesia the projected cost of relocating 3.3 million people was estimated at US$8 billion (From ADB 1994 in Jepma and Munisinghe, 1998). Unfortunately Jepma and Munisinghe do not note the base year of this value, which makes it difficult to compare to other figures.

Case studies of the actual behavioural patterns of individuals living in areas vulnerable to SLR may assist in the development of more realistic adaptation cost estimates. For instance, evidence from the US suggests that individuals do not always willingly relocate even if that is the most cost-efficient alternative and is therefore thought to be “rational” (US Congress, 1993). They often rebuild in vulnerable areas and disregard building restrictions. Moreover, leaving vulnerable areas without protection and simply offering relocation assistance may not be politically viable. On a macro level, the adaptation option of relocation may be viable as people are simply moved from one part of the country to the other. If an assessment is made at the local level with individuals’ willingness to accept and the value of non-market goods taken into consideration, the costs of abandonment may be very high indeed.

3.2.2: Public Infrastructure

The information available about the adaptation costs of climate change for public infrastructure is severely limited. Nevertheless, some cost estimates have been carried out for the UK, and for the cities of Miami, Florida and Cleveland, Ohio, in the US. None of the sources reviewed gives a detailed description of the methodology used to obtain the monetary estimates. The American studies are also very dated. Comparing the cities of Miami and Cleveland does, however, illustrate regional differences in the costs of adapting to climate change.

Walker, *et al.* (in Smith and Tirpak, 1990) conduct a cost analysis of the adaptation measures in the American cities. The costs are assessed by using spatial analogues, critically reviewing previous studies of infrastructure, establishing what the current infrastructure consists of, and questioning local experts about the optimal investment responses given a certain climate scenario. The scenario used is that of a doubling of atmospheric CO_2. The GCM scenarios used are not described, nor are cost estimates obtained for different levels of temperature change, precipitation change or sea level rise.

According to Walker, *et al.,* adapting to climate change will have a neutral effect on the annual operating costs for the city of Cleveland. More severe summers could be accompanied by milder winters. The annual snowfall is expected to drop approximately 1.2 to 2 metres. Roads and bridges might be less susceptible to frost damage. Consequently, the increased costs of air-conditioning and river dredging will be more or less offset by reductions in heating, snow and ice removal and road maintenance and reconstruction. The net cost of these effects is approximately US$1.6 million, depending on the costs of air conditioning (1987 base year). Thus, the city of Cleveland will gradually be able phase out some of its roadwork as winter damage is reduced and provide more air conditioning as the climate gets hotter. Similar circumstances may also prevail in other North American cities.

Miami faces different adaptation costs as it is located in the southern part of the US and is built on coral reefs. Walker, *et al.* warn that Miami is not necessarily representative of coastal cities in general since Miami is completely surrounded by water. An intricate network of canals and levees protect the city from flooding while replenishing the aquifer with water. Climate change is expected to have a substantial impact on Dade County’s water supply, water control and drainage systems, roads, bridges and airports. The adaptation measures needed to accommodate these impacts are expected to cost about US$500 million (1987 base year). This figure presupposes that salt water and fresh water levels will rise gradually, land will be raised, upgraded dikes and levees will maintain sound regulatory functions, people will retreat from vulnerable areas and sufficient freshwater head will be maintained to prevent salt water infusion into the water supply. The impact costs of climate change could be astronomical, if the suggested adaptations are not made on time. Projections specify that the rising water table could destroy 33 percent of Dade County's streets. The airport could be washed away without an improved drainage system and many bridges stand threatened by a one metre sea level rise from their current height.

The methodological approach of the cost assessment conducted in the UK (McKenzie Hedger, *et al.*, 2000) is similar to the one adopted by Walker, *et al.* Specifically, the researchers have drawn heavily on case study experiences and used information from stakeholders and expert judgements. For some estimates, a range of values is used. The discount rate applied is six percent. As noted earlier, discount rates should be used with caution, or eliminated altogether, since they are based on a time preference, which discriminates against future generations. A six percent discount rate is unacceptably high for this reason.

Comprehensive adaptation cost estimates for the infrastructure of the UK have not been assessed. In fact, only the supply and demand for water has been examined in this context. A reduction in water availability is expected to take place in England and Wales. Since the magnitude of the reduction is uncertain, McKenzie Hedger, *et al.* (2000) establish cost estimates for a five percent, a 10 percent, or a 20 percent shortfall in water supply by 2030. Supply side measures include reservoir development, conjunctive use schemes; bulk transfers and desalination. If these options are pursued, a five percent shortfall by 2030 will cost the UK between £1,375 and £2,260 million (base year unknown). A 20 percent shortfall will cost between £5,500 and £49,140. If demand side options are adopted instead, saving five percent and 20 percent of water supplied will only cost £5 or £80 million respectively, depending on the degree of shortfall. Evidently, it is much less costly for households and private enterprises to adjust to shortages by conserving water at the individual level. Degradation of the environment could also be avoided by adopting demand side measures. Of course, a concerted effort would be needed to ensure that households and private enterprises were committed to conserving water. Unfortunately, the "free-rider effect" may limit individual efforts, since there would be the temptation to cheat and use more than the optimal amount of water. The water saved would be a collective good, which would benefit everyone regardless of his or her individual efforts. Economic incentives or regulation measures should consequently be put in place to curb the "free-rider effect".

3.2.3: The Energy Sector

Climate change is expected to impact the energy sector in two different ways. First, energy demand might change due to a different mix of heating and cooling needs. Second, the physical structures associated with energy supply, such as facilities and electrical lines, could be affected by new climate conditions. Regrettably, few, if any, studies examine the latter impacts. The climate change literature does, however, include a few papers on the impacts and adaptation costs of the changes in energy demand associated with climate change. More work must also be done in this area, since there appears to be little consensus concerning the magnitude of the change in demand. Compounded uncertainties also lead to a high net level of uncertainty, which undermines the usefulness of adaptation estimates. Better projections of future climatic and economic conditions should be derived in order to eliminate some of these problems.

Linder and Inglis (in Smith and Tirpak, 1990) found that energy demand would increase substantially under climate change in the US. Hotter temperatures would lead to more frequent use of air conditioning. Space cooling consumes more energy than space heating. Thus energy demand would go up. By 2055, investments to accommodate the increased demand caused by climate change could be between US$200 and US$300 billion (1986 base year). Annual costs might similarly rise by US$33 to US$73 billion. The adaptation costs are positively correlated with the level of temperature increases and economic growth. Impacts and adaptive responses also differ according to region. The increases in energy demand are greatest in western and southwestern North America due to the greater relative importance of cooling costs compared to heating costs in these areas.

Linder and Inglis use the Goddard Institute for Space Studies (GISS) temperature estimates, estimates of the weather-sensitivity of electricity demand, and utility planning assumptions in order to generate a utility planning model, which they then use to estimate the impacts of climate change on utility investments, operations and costs. The GISS bases its temperature predictions on a doubling of atmospheric CO_2. By 2055, the temperature is expected to rise by 3.1 to 5.3 degrees Celsius. For each Celsius degree, the annual energy demand will increase by one percent, and the utility peak demand will expand by 3.1 percent. These figures were estimated by analyzing the effects of normal temperature on electric utilities. Thus temperature change is used as a proxy for climate change.

Morrison and Mendelsohn (in Mendelsohn and Neumann, 1999) use a theoretical–empirical model to establish the impact of climate change on US energy expenditures. They also conduct a climate change simulation that closely resembles that done by Linder and Inglis (in Smith and Tirpak, 1990). According to this simulation, the long run damages of climate change will cost between US$2.4 and US$11.3 billion in 2060, if the climate changes range from 1.5 to 2.5 degree Celsius. In the short run there will actually be benefits of US$1.5 to US$2 billion. The residential sector will experience more of the damages than the commercial sector. The costs of adaptation are also expected to be higher in already hot regions for the same reasons as listed above.

Morrison and Mendelsohn (in Mendelsohn and Neumann, 1999) include an extensive number of variables in their model. They have included expenditure data for different fuels, a whole range of climate variables, demographic characteristics and building characteristics. As indicated, they also make long run and short run analyses. Furthermore, they separate the experiences of the commercial and the residential sectors. The climate change simulation is generated using regression analysis and results are obtained for climate increases of 1.5, 2.5 and five degrees Celsius. Two economic scenarios are also explored. Predicting the population growth, fuel price changes and the level of GDP projects the relevant economic scenario in 2060.

3.2.4: The Agriculture Sector

A search for peer-reviewed articles reveals that little has been done to develop a coherent methodology for estimating adaptation costs specific to the agriculture sector. As Tol, *et al.*, 1998 point out, agricultural studies now routinely include at least some adaptive measures (Adams, *et al.* in Mendelsohn and Neumann, 1995; Darwin, *et al.*, 1995; Mendelsohn, *et al*. 1994, Rosenzweig and Parry, 1994). Unfortunately, they are usually not costed separately. In fact, in many cases the costs associated with adaptation are not included in the analysis at all. That is, it is assumed that adaptation will be costless.

Other articles that discuss adaptation strategies, but without a well-developed analysis of the associated costs, are well summarized in Easterling, *et al.* (1995). Agronomic adaptation strategies outlined include changes in crop varieties and species, timing of operations and land management including irrigation. Economic adaptation strategies include investment in new technologies, infrastructure and labour, and shifts in international trade. The general conclusion, articulated by Easterling, *et al.,* is that such agronomic strategies would be sufficient to either partially or completely offset the loss of agricultural productivity caused by climate change. Economic adaptations were found to render the agricultural costs of climate change small by comparison with the overall expansion of agricultural production.

A pioneering study on farmer adaptation is the MINK study on climate change impacts in the Missouri-Iowa-Nebraska-Kansas region (Easterling, *et al.*, 1993). It uses the climate of the 1930s as an analogue for a possibly drier and warmer future. Besides more technical forms of adaptation, such as crop management practices, the MINK study also considers more institutional forms of adaptation, such as distribution of water resources. Using an arbitrary set of low-cost adaptation measures, like a change in planting date or increased irrigation, Easterling, *et al*. calculate that adaptation costs could reduce agricultural damages to the MINK region by 30 to 60 percent.

According to Tol, *et al*., other studies show a similar picture. Rosenzweig and Parry (1994) distinguish three arbitrary levels of adaptation. In the “without adaptation” scenario, farmers continue to behave as they currently do, that is, they completely ignore that climate has changed. Under “level 1 adaptation”, small adjustments in behaviour and modest capital investments (within the capacity of an individual farm) are allowed. “Level 2 adaptation” assumes large adjustments and investment. In their global study, a change of –1.2 to – 7.6 percent in worldwide cereal production without adaptation is reduced to 0 to –5 percent with moderate farm level adaptation. This could reduce global welfare loss of US$0.1 to US$61.2

billion without adaptation, to between a gain of US$7.0 billion and a loss of US$37.6 billion (Reilly, *et al*., 1994). As Tol points out, the shortcoming of these studies is that while the benefits of adaptation (avoided impacts) can be derived from these models, the costs of adaptation (such as investments costs) are neglected. Even though high levels of adaptation are assumed to be costly, precise costs are not reported or included in the impact estimates cited above.

Mizina, *et al.* (in Smith, *et al.*, 1996) examine the impact of climate change on wheat crops in Kazakhstan. They also measure some of the costs associated with adapting to new climatic conditions. Comparing local adaptation costs to the cost of importing wheat, they find that it is most economically efficient to respond to wheat yield reductions by adopting new agricultural practices. Different strategies are recommended at the national and the local level. At the national level these strategies include (1) educating the public, (2) sponsoring research projects, which are directed toward examining agricultural vulnerability and developing new wheat strains, (3) planting forests and (4) planting perennial vegetation. At the local level, farmers in Kazakhstan may respond to climate change by (5) expanding irrigation facilities, (6) changing sowing dates, (7) planting more winter wheat, (8) increasing fallow percentage, (9) using new wheat varieties, (10) increasing the usage of fertilizer and pesticides and (11) utilizing zonal growing technology. Mizina, *et al.*only provide costs for half of these adaptation options. How the cost estimates are derived is not explained, except in the instance of tree planting where the costs are based on a tree planting project that was implemented in Kazakhstan in 1994.

Mizina, *et al.* indicate the possibility of funding each strategic measure. Thus, funding is “impossible”, “impossible without international subsidies”, “possible under general economic improvement” or “ possible through Kazakhstani efforts”. Not surprisingly, the level of affordability is negatively correlated with the magnitude of costs for each option. The expected yield increase and the effects associated with the local strategies are also listed. The additional forests needed to help regulate the hydrological cycle, and reduce the aridity caused by climate change, are expected to cost US$3.5 million (base year 1994). Some of this money must be financed internationally. Planting perennial vegetation will similarly reduce aridity by locking moisture into the ground. This project, which is estimated to cost US$1.2 million (base year 1994), will also maintain the quality of the soil. Increasing fallow land would cost about US$15.62 per tonne of wheat. However, this adaptive response is not economically beneficial. Other sectors of the economy would probably get more value added for the area used. Using higher yielding, drought-resistant, earlier maturing, disease- and pest-tolerant wheat varieties could cost US$1.19 per tonne. The beneficial effect of this measure is enormous at US$16.63 per tonne. Unfortunately the people of Kazakhstan will only be able to afford new wheat varieties if the economy continues to improve. Fertilizers, pesticides, and weed control are more costly and less economically beneficial. In fact, the costs, at US$25 per tonne, are twice as high as the benefits of US$8 to US$13 per tonne. The respective costs and benefits for zonal growing technology are US$70 per tonne and US$8 per tonne. Nevertheless, adopting these options will still be advisable, since winter wheat costs US$80 to US$100 per tonne and spring wheat costs US$100 to US$130 per tonne on the international market. Furthermore, there are non-market "goods" that come along with domestic agricultural production such as employment opportunities and social stability. As mentioned earlier, Mizina, *et al.* maintain that any adaptive measures for Kazakhstan will be preferable to the purchase of wheat abroad. However, a thorough economic argument to support this statement is not provided.

Canadian governments have considerably more funds available to help the agricultural sector adapt to normal and changing climate conditions. In 1996/97 the Agricultural Research Institute of Ontario (ARIO) received CAN$42,356,784 from the Ontario government for research purposes (ARIO, 2000). The year earlier (1995/96) the federal government earmarked CAN$276.1 million for the Research Branch of Agriculture and Agri-food Canada (2000). According to the 1995/96 budget, 52 percent of these funds were to be spent on crop research and 19 percent were to be spent on resource conservation research.

The Research Branch Advisory Committee (RBAC) expresses commitment in the following areas:

- Controlling crop disease
- Controlling pests
- Breeding for resistance to stresses
- Preserving natural resources

Crop diseases can be caused by a number of different variables, many of which are expected to change with the climate. These include pathogens such as bacteria, fungi, viruses and various other single-celled organisms. Physiological disorders of crop plants may be produced by the stress induced by higher temperatures, drought and competition from weeds. As mentioned earlier, the Canadian climate will most likely become hotter, more humid and sustain heavier precipitation. With increased heat and humidity, conditions will be ideal for many agricultural pests and diseases as well as for agricultural products themselves. Adequate control measures for all forms of agricultural pests and diseases do not currently exist for all crop plants; the potential for huge losses due to climate-induced plagues and epidemics is high. The loss of extreme winter conditions will reduce the winterkill for perennial plants but it will also decrease the mortality in insect pests and fungal spores. Increased climate variability will put considerable stress on plants. Many agricultural crop cultivars are poorly equipped to handle drought, disease and pests as they have been bred for yield and not durability. The impact of increased heat stress and the proliferation of pests and diseases on animal agriculture may be as high as the impact on plant agriculture. Increased fungal contamination of feed due to high humidity will add to the malaise for livestock that is directly created by climate change.

Although none of the aforementioned research money is explicitly being used to adapt to climate change, current research may nonetheless reduce its effects. Of course, a separate research agenda to address climate change is still in order. At the moment, climate change is not even mentioned in the 53-page business plan of the Research Branch (Agriculture and Agri-food Canada, 2000). Climate change may also necessitate an expansion of Canadian expenditures on agricultural research and development. This extra research capacity should exist. In 1988, only two percent of the Canadian agricultural gross domestic product was being invested into research and development compared to two to four percent for countries in Western Europe, Japan and Australia.

Smit (in Etkin and McColloch, 1994) maintains that government subsidies to agriculture represent both:

a) A response to climate variability and extremes

b) A modifier of effects and hence adaptation to climate.

Moreover, Smit illustrates how federal and provincial (Ontario) government payments related to climate variability increased dramatically from 1972 to 1992. The effects of climate change are not specifically isolated in Smit’s analysis. However, increasing the amount of agricultural subsidies can be viewed as a potential response option to climate change. In other words, Canada adapts by allowing Canadian taxpayers to absorb many of the impact costs. Although this policy may be beneficial to the extent that it spreads the increased risks associated with climate change, it also could lead to excessively risky, sub-optimal, behaviour and a low level of adaptation at the individual level. Farmers might not invest the optimal amount of money into adapting to climate change since the impact costs they experience do not warrant such investments. In economic terms, when the impact costs are absorbed by society in general, the marginal benefit of adaptation is reduced for the individual. A lower level of protection, in turn, leads to a higher level of impact costs for the Canadian public. A transfer of funds from direct agricultural subsidies to investment in research and development could reduce this effect.

On July 5, 2000, the Canadian Agriculture and Agri-food minister, Lyle Vanclief, announced a new CAN$5.5 billion National Safety Net Agreement, which will cover Canadian farmers for the next three years (Minister's Statement, 2000). According to Vanclief, this money will be used to fund the most comprehensive safety net package to date. The horizon for this safety net is obviously short and is designed largely to shield farmers from the (short term) low international market prices. What is needed is a clear recognition of the need to adapt, with a long-term perspective in mind.

For the US, the impact costs of climate change in the agricultural sector were originally estimated without taking adaptation into consideration. Mendelsohn, *et al.* (1994) point out this major omission, which they are quick to correct in the paper titled, "The Impact of Global Warming on Agriculture: A Ricardian Analysis". Incorporating adaptive responses into the impact literature is an important first step toward estimating the costs and benefits of adaptation. It pushes the study of adaptation forward. A comparison of impact estimates showing the difference between the estimates that include and those which exclude adaptation measures also illustrates the substantial benefits associated with efficient adaptation (Mendelsohn, 2000). In Mendelsohn, *et al.* (1994), the net benefit of adapting US agriculture to climate change is between US$7 and US$11 billion (1982 base year).

Unfortunately, these figures do not take the costs of adaptation into account. The farmer is expected to switch to new crops, to use different technology, to start raising livestock or to plant forests without incurring any adjustment costs. If these activities are not sufficiently lucrative, the farmer can simply sell his land to developers, who will convert it into cities, retirement homes, campsites and other productive uses. If economic substitution takes place, the use of the land will be determined by the value of each activity given the particular climatic and environmental conditions. According to the Ricardian approach being used, changes in economic activities will be facilitated through the land market at no cost. Mendelsohn, *et al.* (1994) illustrate how land originally used for growing wheat could be used to grow corn as the climate warms. It could then be used to graze cattle, as the climate becomes drier. Finally, the site could be used for a retirement home, as the temperature becomes too hot and dry to sustain agriculture. Switching activities in this manner would probably be a very expensive enterprise. For instance, new investments into machinery and technology would have to be made if different crops were planted, farm buildings would have to be retired and new facilities would have to be built to support new activities. The social costs would probably be high as well. For instance, many farming communities will have to change their primary activities and perhaps even give up their previous ways of life altogether. All of these adaptation costs should be taken into consideration when assessing the feasibility of suggested changes in adaptive use of land.

The impact of a change in climate is derived assuming that future farmers have similar motives and similar constraints as present day farmers. Tol, *et al.* (1998) point out that while the former assumption seems reasonable, some of the constraints faced by farmers are likely to change through changes in the food market and through deliberate policies. These effects are not explicitly spelled out and are essentially hidden in the "black box" of currently observed behaviour. Darwin, *et al*. (1995) use a similar method but they supplement the usual black box by coupling an analogue model for crop yields and farmer behaviour (for the entire world) with a trade model for food products. With such a coupled model, autonomous adaptation can be studied. In addition, the effect of policies such as income support or price subsidies can also be analyzed.

Adams, *et al.* (in Mendelsohn and Neumann, 1999) also expect farmers to adapt to climate change when it occurs. The mitigating effects of adaptive responses are thus included in the impact costs, which they estimate for the US agricultural sector. Specifically, Adams, *et al.* advance impact literature by:

> (1) Incorporating other crops such as fruits and vegetables into the regional crop alternatives for the southeast and other southerly locations: (2) Considering the impacts of additional farmer adaptations to climate change; (3) Allowing for crop migration into regions where those crops are not currently being grown; (4) Incorporating changes in forage production and livestock performance; [and] (5) Assessing the potential of technological change, as manifested in present and future yields to offset climate change." (Adams, *et al.*, in Mendelsohn and Neumann, 1999, p.20)

Unlike Mendelsohn, *et al.* (1994), Adams, *et al.* do not expect farmers to switch away from farming altogether. The two studies are, however, similar to the extent that they do not include the costs of adaptation.

Adams, *et al.* include adaptation responses in the agricultural sector model (ASM), which they use to project the net welfare impacts of climate change. Two separate approaches are used for this purpose. One approach examines the ability of crops to migrate and the role of agricultural research. The other approach attempts to establish how agricultural yields are affected by changes in temperature and precipitation. Both approaches rely on regression analysis for their results. The latter approach is based on neoclassical duality theory. A range of different variables, including those previously mentioned plus soil characteristics and output prices, is also incorporated into the ASM.

According to Adams, *et al.*, the cumulative effect of adaptation options is a 50 percent reduction in negative yield changes under the 2.5 degree Celsius scenario and a 25 percent reduction under the five degree Celsius scenario. These offsetting effects translate into a US$7 billion (1990 base year) increase in welfare using 2060 economic projections under the most severe climate scenario. Under milder scenarios, the impact is negligible. Under the central case with a 2.5 degree Celsius increase in temperature and a seven percent increase in precipitation, welfare is expected to increase by US$47 billion (1990 base year). This estimate includes the fertilization effect of CO_2.

The study conducted by Adams, *et al.* (in Mendelsohn and Neumann, 1999) has many of the same deficiencies as the one by Mendelsohn, *et al.* (1994), especially to the extent that the costs of adaptation are not accounted for. The omission of research costs is particularly glaring in the former study. As the description of agricultural research in Canada indicates, these costs may be considerable. Other costs of adaptation in the agricultural sector may include:

- Investments in agricultural technology
- The funds needed to develop new equipment
- The cost of disseminating information
- Education costs
- The cost of climate information
- Higher per unit costs of water

Misguided efforts to mitigate the effects of climate change will increase the magnitude of these costs. Thus, more research on this topic is needed in order to reduce the current level of uncertainty.

A survey of the peer reviewed literature has shown that most of the material on the costs and benefits of adaptation in the agriculture sector has been collected within the context of analyzing the impact of damages. In particular, most studies tend only to estimate the benefits of adaptation but do not fully account for its cost, especially when complete changes in behaviour, infrastructure and institutions have been contemplated. Tol, *et al.* (1998) emphasize that while climate change impacts will be reduced in a fully adapted society, the process of reaching this level could be costly and success may depend on adequate planning and suitable policy measures.

3.2.5: Forestry

A search of the peer-reviewed literature indicates that only two papers dealing with the costs of adaptation to climate change in the forestry sector appear to have been published to date. The first, by Sohngen and Mendelsohn (in Mendelsohn and Neumann, 1999), examines the timber market impacts of climate change on US forests. Although it does not estimate adaptation costs and it was necessary to deduce the value of benefits, it represents one of the first attempts to understand the process of adaptation and the costs of transition in the forestry sector. This study underscores the important role of information and hence gives some insight into the transitional impacts. If foresters are taken by surprise when forest-stands suffer from dieback, net present benefits of climate change range between US$2.2 and US$16.2 billion; if, however dieback is foreseen, benefits range between US$4.9 and US$17.3 billion (1982 base year). Both estimates assume that foresters can predict climate change well enough to plant the right type of trees. If foresters do not have perfect foresight, net present benefits range from –US$4.3 to US$11.7 billion if dieback occurs as a surprise and –US$0.4 to US$13.9 billion there is no dieback surprise (1982 base year).

In their article, "Climate Change and Forestry: What policy for Canada?", Stennes, *et al.* (1998) discuss adaptation but do not provide any estimates as to the cost. If we accept the results of the Future Agricultural Resources Model (FARM) used by Darwin, *et al*. (1995), then these authors indicate that adaptation will ensure that forest returns are maximized. The FARM model predicts that forestry and agriculture will be net gainers from climate change (at least in terms of productivity) and that adaptation will involve a shifting of land out of forestry and into agriculture. Production of wheat, other grains, non-grains and livestock are all expected to increase with climate change. Forestry output is also expected to increase although the area of forestland is reduced. Stennes, *et al.* outline some of the potential adaptation strategies that may be used in the forestry sector. These include: salvaging dying trees; vegetation control to offset drought; replanting with more suitable species and shifting processing capacity to areas where timber is relatively plentiful.

As was the case with the agricultural sector, there is little in the peer-reviewed literature that points to a clear methodology for estimating adaptation costs in their own right for the forestry sector.

3.2.6: Summary of Empirical Estimates of Adaptation Costs

1. One of the main consequences of climate change will be sea level rise, and adaptation will require coastal protection. For Canada, one author estimates that the optimal protection level in Canada is 26 percent. The total cost of adaptation is estimated at US$6.92 billion (in present value terms, 1990-2100) based on a 26 percent protection rate

of Canada's open coasts and a 40 percent protection rate of Canadian beaches.

2. For the US, coastal protection will cost US$500 to US$2,600 per metre, and sea wall and bulkhead are US$500 to US$13,200 per metre (base year 1990). The baseline results for both categories are US$2,500 per metre (base year 1990). Maintenance costs are four and 10 percent for soft and hard structures respectively. The magnitude of fixed and variable costs vary depending on the sea level rise projected. Another estimate reduces the cost to between US$100 and US$200 million per year for the US, using a three percent discount rate. These estimates are obtained by aggregating data from all the coastal areas. They are lower than previous US estimates, since the precision of the computer-mapping method allows abrupt contours that protect property to be taken into account.
3. Nicholls and Leatherman (in Strzepek and Smith, 1995) examine the impact and adaptation costs of accelerated SLR for Argentina, Nigeria, Senegal, Uruguay and Venezuela. For each country, they assess the level of vulnerability, the per unit cost of beach nourishment, sea walls and harbour upgrades, and the appropriate mix of coastal defence measures depending on the response option chosen. The costs of protection, on the other hand, consist of fixed and variable costs.
4. The costs of coastal protection vary depending on which response is chosen. The magnitude of the sea rise is also positively correlated with total costs. In this study, the highest costs are associated with Uruguay. These costs are estimated at US$2070 to US$2142 million for protecting important areas, and US$2155 to US$2729 million for total protection for the 0.5 metre sea level rise, and US$2905 to US$2995 million for important area protection and US$3126 to US$3793 million for total protection for the

one metre sea level rise. About six percent of gross investment (the money available for investment) in Uruguay currently consists of coastal protection costs. This percentage is expected to increase under accelerated sea level rise scenarios unless economic development offsets this effect.

5. The information available about the adaptation costs of climate change for public infrastructure is severely limited. Nevertheless, some cost estimates have been carried out for the UK, and for the cities of Miami, Florida and Cleveland, Ohio, in the US. None of the sources reviewed gives a detailed description of the methodology used to obtain the monetary estimates. The American studies are also very dated.
6. Comprehensive adaptation cost estimates for the infrastructure of the UK have not been assessed. In fact, only the supply and demand for water has been examined in this context. A reduction in water availability is expected to take place in England and Wales. Since the magnitude of the reduction is uncertain, British researchers establish cost estimates for a five percent, a 10 percent, or a 20 percent shortfall in water supply by 2030. Supply side measures include reservoir development, conjunctive use schemes; bulk transfers and desalination. If these options are pursued, a five percent shortfall by 2030 will cost the UK between £1,375 and £2,260 million (base year 2000). A 20 percent shortfall will cost between £5,500 and £49,140 million. If demand side options are adopted instead, saving five percent and 20 percent of water supplied will only cost £5 or £80 million respectively, depending on the degree of shortfall. Degradation of the environment could also be avoided by adopting demand side measures.
7. Climate change is expected to impact the energy sector in two different ways. First, energy demand might change due to a different mix of heating and cooling needs.

Second, the physical structures associated with energy supply, such as facilities and electrical lines, could be affected by new climate conditions. Regrettably, few, if any, studies examine the latter impacts. The climate change literature does, however, include a few papers on the impacts and adaptation costs of the changes in energy demand associated with climate change.

8. For the US, the literature shows that energy demand would increase substantially under climate change in the US. Hotter temperatures would lead to more frequent use of air conditioning. Space cooling consumes more energy than space heating. Thus energy demand would go up. By 2055, investments to accommodate the increased demand caused by climate change could be between US$200 and US$300 billion (1986 base year). Annual costs might similarly rise by US$33 to US$73 billion. Impacts and adaptive responses also differ according to region. The increases in energy demand are greatest in western and southwestern North America due to the greater relative importance of cooling costs compared to heating costs in these areas. Based on a doubling of atmospheric CO_2, by 2055, the temperature is expected to rise by 3.1 to 5.3 degrees Celsius. For each Celsius degree, the annual energy demand will increase by one percent, and the utility peak demand will expand by 3.1 percent. These figures were estimated by analyzing the effects of normal temperature on electric utilities. Thus temperature change is used as a proxy for climate change.

9. According to another simulation for the US, the long run impact of climate change will cost between US$2.4 and US$11.3 billion in 2060, if the climate changes range from 1.5 to 2.5 degrees Celsius. In the short run there will actually be benefits of US$1.5 to US$2 billion. The residential sector will experience more of the costs than the commercial

sector. The costs of adaptation are also expected to be higher in already hot regions for the same reasons as listed above.

10. In agriculture for North America, agronomic adaptation strategies such as changes in crop varieties and species, timing of operations and land management including irrigation, would be sufficient to either partially or completely offset the loss of agricultural productivity caused by climate change. Economic adaptations were found to render the agricultural costs of climate change small by comparison with the overall expansion of agricultural production.
11. Canadian governments traditionally help the agricultural sector adapt to normal and changing climate conditions. In 1996/97 the Agricultural Research Institute of Ontario received CAN$42,356,784 from the Ontario government for research. The year earlier (1995/96) the federal government earmarked CAN$276.1 million for the Research Branch of Agriculture and Agri-food Canada . According to the 1995/96 budget, 52 percent of these funds were to be spent on crop research and 19 percent were to be spent on resource conservation research. In Canada, the Research Branch Advisory Committee (RBAC) expresses commitment in the following areas: controlling crop disease, controlling pests, breeding for resistance to stresses, and preserving natural resources. Crop diseases can be caused by a number of different variables, many of which are expected to change with the climate. These include pathogens such as bacteria, fungi, viruses and various other single-celled organisms. Physiological disorders of crop plants may be produced by the stress induced by higher temperatures, drought and competition from weeds. As mentioned earlier, the Canadian climate will most likely become hotter, more humid and sustain heavier precipitation. With increased heat and humidity,

conditions will be ideal for many agricultural pests and diseases as well as for agricultural products themselves. Adequate control measures for all forms of agricultural pests and diseases do not currently exist for all crop plants; the potential for huge losses due to climate-induced plagues and epidemics is high. The loss of extreme winter conditions will reduce the winterkill for perennial plants but it will also decrease the mortality in insect pests and fungal spores. Increased climate variability will put considerable stress on plants. Many agricultural crop cultivars are poorly equipped to handle drought, disease and pests as they have been bred for yield and not durability. The impact of increased heat stress and the proliferation of pests and diseases on animal agriculture may be as high as the impact on plant agriculture. Increased fungal contamination of feed due to high humidity will add to the malaise for livestock that is directly created by climate change. Although none of the aforementioned research money is explicitly being used to adapt to climate change, current research may nonetheless reduce its effects.

12. For forestry in the US, the review of the literature shows that if foresters are taken by surprise when forest-stands suffer from dieback, net present benefits of climate change could range between US$2.2 and US$16.2 billion; if, however dieback is foreseen, benefits range between US$4.9 and US$17.3 billion (1982 base year). Both estimates assume that foresters can predict climate change well enough to plant the right type of trees. If foresters do not have perfect foresight, net present benefits range from –US$4.3 to US$11.7 billion if dieback occurs as a surprise and –US$0.4 to US$13.9 billion there is no dieback surprise (1982 base year).

13. For Canada, if we accept the results of the Future Agricultural Resources Model

(FARM), then their authors indicate that adaptation will ensure that forest returns are maximized. The FARM model predicts that forestry and agriculture will be net gainers from climate change (at least in terms of productivity) and that adaptation will involve a shifting of land out of forestry and into agriculture. Production of wheat, other grains, non-grains and livestock are all expected to increase with climate change. Forestry output is also expected to increase although the area of forestland is reduced. Some of the potential adaptation strategies that may be used in the forestry sector include: salvaging dying trees; vegetation control to offset drought; replanting with more suitable species and shifting processing capacity to areas where timber is relatively plentiful.

3.3: Estimates from the United Kingdom

The UK has shown a particular interest in establishing the impacts and adaptation costs of climate change. This does not come as a surprise as the UK experienced its hottest year in recorded history in 1999 and it is particularly vulnerable to potential changes in sea levels as an island nation. This section is a review of two recent publications distributed by the UK government on potential adaptation strategies for climate change.

The UK Climate Impacts Program (UKCIP) recently published "Climate Change: Assessing the Impacts-Identifying Responses" (McKenzie Hedger, *et al.*, 2000). This publication summarizes some of the key findings by the UKCIP to date. These highlights are mostly derived from scoping studies that have been completed for Scotland, Wales, northwest England, southeast England and southwest England. These scoping studies derive their information from pertinent literature, expert judgements and interviews with key stakeholders (McKenzie Hedger, *et al.,* 2000). The methodology is thus comprehensive, as it includes several methods of data collection and is based on stakeholder involvement in the process.

Comparing these studies highlights various regional similarities and differences regarding the impacts of climate change in the UK. Based on the current findings, it appears that most areas will be threatened by increased flooding and other problems associated with sea level rises. But of course this fate can be expected by all island nations, including the UK. Different ecosystems and various forms of wildlife are also negatively impacted by climate change regardless of the region in question. To highlight regional differences, the potential impacts of climate change on Scotland and southwest England will be compared.

In Scotland, the heavier rainfall might cause reservoir overspill during the winter, whereas southwest England could have water supply problems due to summer droughts. Southwest England could also lose its regional advantage for growing crops while Scotland's forest industry could benefit from climate change. Scotland's winter sports industry, on the other hand, may not survive global heating. Higher temperatures, however, could attract more tourists to the beaches in southwest England. As far as buildings and cultural heritage are concerned, houses in Scotland might be damaged by damper weather conditions, at the same time as historic gardens in southwest England will suffer from droughts (McKenzie Hedger, *et al.*, 2000). Negative impacts can thus be expected in both regions, but they will be caused by different variables. These findings are consistent with Canadian studies that predict large regional differences in the impacts of climate change. Adaptation measures will have to take these local particularities into account if they are going to be effective.

The scoping studies analyze the potential impacts of climate change at the regional level. "The Potential Adaptation Strategies for Climate Change" (Department of the Environment, Transport and Regions, or DETR, 2000), on the other hand, examines the adaptation options available to different sectors of the UK. Moreover, the UK is at a fairly advanced stage of establishing the sectoral adaptation costs of climate change. Nevertheless, the British cost estimates are "preliminary in nature" according to the government itself (DETR, 2000). The DETR consequently suggests that more inclusive estimates should be developed in the future that have better parameters of certainty, include all the affected sectors and are comparable across sectors. The current study includes potential adaptation responses and cost estimates for water resources, flood protection, buildings and infrastructure and nature conservation. The relative importance of different vulnerable areas was established based on scientific and economic analysis and subjective judgement. In other words, the sub-sectors that have a high economic, biological, or social value are deemed worth saving. Thus only the costs of adapting them to climate change are estimated. A six percent discount rate is used over a 30-year period to establish the costs and benefits of adaptation. The costing data are based on case study analysis, input from stakeholders and expert opinion. The methodology used is similar to the one used for the scoping studies previously mentioned. The DETR (2000) reports difficulties in estimating the environmental and social costs of climate change. This is a problem that many researchers wrestle with.

The DETR (2000) expects coastal and riverine flooding to double or triple over the next 50 years as a direct result of climate change. Sea level rises, increased precipitation, and more extreme events will consequently cause two to three times more flood damage than the UK is currently experiencing. Whether this figure takes into account adaptation measures is unclear. Adapting to the increased frequency in riverine flooding is expected to cost £24.5 million per year (base year 2000) for 50 years in England and Wales and an additional £19 million would be required each year for 10 years in Scotland. Coastal flood adaptation measures are expected to cost £50 million per year for 50 years for England and Wales. An additional £1.25 million per year would be required for 10 years for Scotland. Some of the costs of damages and adaptation measures associated with flooding will be absorbed by insurance companies, national governments and local governments. These costs will eventually be passed on to taxpayers and insurance policyholders.

The DETR (2000) proposes three actions based on a "no regrets policy" to curb the damages imposed by increased flooding. They are as follows:

- Identify areas vulnerable to flooding.
- Encourage effective adaptive behaviour.
- Discourage development in high-risk areas. Improved identification strategies, public education, and better urban planning will contribute toward these actions.

Many of the climate changes envisioned by UKCIP will affect buildings and infrastructure externally, leading to increased vulnerability to extreme events and eventually damage to internal conditions. For example, wetter winters are expected to increase condensation and mould growth. In response, the DETR advocates building "climate headroom" into standards and regulations for new buildings and infrastructure and retrofitting and refurbishing existing stock. A preliminary analysis suggests a one to five percent increase in current construction costs to meet these challenges. This is projected to lead to costs of £3.6 to £26 billion (base year 2000) aggregated over the building stock. These costs will be absorbed initially by building owners and service providers who will pass them on to tenants. In the case of buildings and infrastructure, the DETR indicates the following "no regrets" actions:

- Incorporate "climate headroom" into building standards and regulations
- Raise awareness of the importance of retro-fitting and refurbishment

The DETR carries out an analysis of potential adaptation responses in the area of nature conservation that focuses on coastal habitats, sand dunes, salt marshes, mudflats, saline lagoons and beaches. These areas are considered to have high conservation value. In the DETR's view, key climate impacts are likely to include:

- The species in half of all designated areas may be significantly affected by a one degree Celsius increase in mean annual temperature.
- Due to temperature increases, rainfall and sea level and storm surges, 25 percent of designated habitats could be lost at a linear rate to the year 2030.

Of course, there is considerable uncertainty as to how species and habitats will react. Potential adaptation responses include:

- Reliance on natural migration processes
- Facilitation of colonization processes by removing barriers to ecological processes
- Re-creation or restoration of habitats under threat

Clearly, different levels of intervention imply different costs; the DETR estimates potential adaptation costs of £150 to £1400 million (base year 2000), depending on level of intervention. Again, costs are given in net present value terms discounted at a rate of six percent per annum. "No regrets actions" in the area of nature conservation are as follows

- Improve protection and management of existing designated areas
- Ensure policy builds on the natural dynamics of ecosystems and incorporates buffer zones in designated areas
- Incorporate opportunities to facilitate colonization in agri-environment schemes, flood defence schemes and coastal planning

Our main interest in reviewing these UK studies is twofold. First, we are interested in what are judged to be the key considerations in developing an adaptation strategy. Second, and more importantly, we are interested to see just what methods were used to arrive at adaptation cost estimates. Although this report was published recently (May 2000), its cost estimation methods are not clear and the analysis is compromised by the use of high discount rates. Like most other quick and dirty methods, the UK methodology has major limitations due to the uncertainties surrounding climate change impacts, the problems of valuing environmental and social damage and the use of discounting. Discounting, by its very nature, encourages little adaptive action as the benefits of adaptation are grossly underestimated. Nevertheless the UK studies deserve closer examination and comparative study.

Part 4: Synthesis

In this part of the literature review we first summarize what we have learned from the literature in terms of the development of a practical estimation of adaptation costs. We then outline a concrete research program for the future.

4.1: Lessons from the Literature for Empirical Estimation of Adaptation Costs

The objective of doing this literature review of adaptation costs was to answer two questions: (1) What is known about the theory and estimation of adaptation costs to climate change? (2) In view of what is known, what remains to be done in order to develop a complete template of adaptation costs?

On the key question of how much to adapt, the guiding principle in the literature is "adapt up to the point where the incremental benefits just equal the incremental costs". This is what we have called the MB = MC rule, a rule which is often recommended for environmental remediation and compensation. This rule is endorsed by the leading climate change economists.

It is also endorsed by UNEP, although in our opinion, the UNEP methodology is, in general, better. The standard MB = MC rule is applied at a high level of abstraction, which may be inappropriate for policy purposes. The high level of abstraction implicitly or explicitly assumes that:

(1) Climate change can be viewed as a purely *local* phenomenon (like an oil spill or a hazardous waste disposal problem).

(2) Climate change is a marginal and an additively separable “project”.

(3) The benefits of adaptation to climate change can be valued in the same way as the valuation of a consumption good, with the marginal utility of adaptation declining with increased expenditure on adaptation; that is, the benefit function is strictly concave.

(4) The costs of adaptation increase at an increasing rate; that is, the cost function is convex to the origin.

The four assumptions listed above, including the concavity of the benefit function and convexity of the cost function, guarantee a unique equilibrium that is dubbed “efficient”. This makes climate change a purely local phenomenon, whereas most climate change scientists would agree that climate change is a global externality, affecting the entire biosphere. A global externality cannot be “internalized” by a level of adaptation at which MB = MC. The ozone hole was, and is, a global externality and the appropriate response to that externality was the phasing out of all ozone depleting substances, as stated in the much revised Montreal Protocol.

While it is true that the counterpart of the Montreal Protocol is the UNFCCC, and the Kyoto Protocol, which are efforts in the direction of mitigating climate change, it is clear that the world will have to learn "to live" with climate change. It is also true that the benefits of adaptation will be local and therefore countries should press ahead with adaptation, as any implementation of mitigation policies is likely to be slow. But the adaptation will still be to a negative externality, or a global public “bad” (a negative public good). If it is accepted that the appropriate framework is that of the optimal provision of public goods, then the four assumptions stated above need to be relaxed and a new methodology for the optimal level of adaptation to climate change needs to be articulated. We plan to do just that in our next submission. We hope to show that the optimal adaptation will be based in a theory of investment in a context of preserving natural and human-made capital. Thus we shall shift the focus from consumption benefits to a theory akin to portfolio choice in the theory of finance. Specifically, our aim will be to show that the optimal adaptations will be a function of the climate change *scenarios*, and not on the level of theoretical abstraction. The uncertainty or variation in the level of adaptation must depend on statistical properties of climate change and not be based on treating climate change as a marginal project.

Part Three of our review shows that there have been some attempts, at a high level of abstraction, to estimate adaptation costs in Canada. These estimates are unstable, however, and are highly sensitive to the assumptions underlying the level of abstraction. For example, one author’s result for the total adaptation to climate change for North America changed from a total cost (or loss) of US$30 billion to a net welfare *gain* of US$175 billion, which is about 3.4% of North American GDP. In this estimate, there are “gains” in agriculture, forestry and nature (ecosystems, species and landscapes). The losses are due to sea-level rise, changes in the value of wetlands, population migration, increased energy demand, changes in water resource availability and increases in mortality due to the northward migration of tropical diseases. It is not clear whether the author was referring to climate change impact costs or to adaptation costs.

If the net gain estimate is true, then climate change is not a cost; it is, in fact, a net benefit and should be welcomed. But we already know ahead of time that climate change will *change* the distribution of the ecological services provided by the natural capital of the biosphere (what we call "perpetual dividends"). Therefore, there may be some gains in agriculture and forestry, but even within agriculture and forestry, we can expect some costs in agriculture due to droughts, and costs in forestry due to increased frequency and intensity of forest fires and insect damage. Thus, climate change is all about the distribution of the perpetual dividends, which may not be all that perpetual if there is damage to some forms of natural capital *beyond* the threshold of recovery.

Our infrastructure that includes *inter alia* roads, bridges and power lines have all been built to engineering specifications appropriate to a *given* climate, with a given range of variability. Taking into account the mean and also the variability is of course the defining characteristic of a distribution. If the distributions all change, then the infrastructure will have to be adapted to a new distribution of climate. Thus, from a micro perspective, climate change will impose costs of adaptation on many things we take for granted, from our driveways to ports and harbours to power supply. Canadians in eastern Canada received a rude awakening when the 1998 ice storm (the worst in Canadian history) occurred. This natural disaster was probably connected to climate change, although we won't know for certain for some time yet. Whether climate change delivers net gains at the aggregate level of GDP is yet to be seen.

From a perspective of "no regrets policy" and the precautionary principle, it is best not to bank on gains from climate change at the aggregate level. Instead, it would be wise to concentrate on the micro level and attempt to estimate adaptation costs. This can be done by (1) relaxing the four assumptions previously stated and (2) building a systematic record of physical adaptations and their respective costs, sector by sector. This is exactly what we intend to do.

The next section outlines a logistical plan for carrying out this research.

4.2: Directions for Future Research

In this section we discuss a logistical plan for developing a consistent methodology for estimating the costs of adaptation to climate change and developing a template for each sector for each climate change scenario. We organize this projected work as a multi-year research proposal.

Scientists and policy makers have chosen to discuss their response to climate change in terms of "mitigation" and "adaptation", although any successful attempts at slowing down climate change (mitigation) will clearly affect actions required to come to terms with climate change (adaptation). Any benefits in mitigation policies will be global and will only succeed if an internationally agreed policy is implemented. On the other hand, for many nations, the costs and benefits of adaptation are almost entirely "national" and local. This may not be true for the US, which is a very large emitter of GHGs, but it is certainly true for all countries, including Canada, which have either a small population or a small economy. The Climate Change Secretariat is no doubt aware that climate change will impose varying costs. These impact costs will be very unevenly distributed within Canada. This unevenness could impose periodic catastrophic losses on particular communities of Canadians. For example, climate change could increase the intensity and severity of El Niño events, which would affect many parts of the world. At least a few scientists have linked the 1998 ice storm in eastern Canada to climate change. As stated above, this ice storm was the most severe climate related disaster in the history of Canada; its cost has been conservatively estimated at CAN$4.2 billion (Dore and Etkin, forthcoming). Similarly, as a result of climate change, we can expect huge impact costs unless Canadians (a) have the necessary information on possible impact costs, and (b) are ready to incur the required adaptation costs as an investment to avert the most severe of the climate change impact costs.

The Climate Change Secretariat should commission and finance the required research to meet the twin objectives of estimating the possible climate change impact costs and determining the optimal adaptation investments that should be undertaken to come to terms with climate change. With this in mind, we have developed a three to five year plan for a systematic and consistent approach to estimating both the costs of climate change impacts and the necessary adaptation costs.

It is important that such research be well planned, time-phased, have a consistent set of impact costs and use consistent definitions of adaptation costs. This must also remain consistent with climate change scenarios that have been generated by the Climate Change Centre at the University of Victoria. There can be no substitute for a three to five year systematic inquiry that meets the twin objectives mentioned above. The research must be operationally useful to Canadian consumers, public agencies and private businesses. If utilized correctly, the results of the research should put Canadian business at a competitive advantage and soften or prevent the incursion of large costs for the public sector that so often characterize extreme climatic events. That is the most positive role that the Climate Change Secretariat can play. That is also the highest return that the research can offer to Canada.

A review of the literature shows that most costs of adaptation to climate change are guesstimates of aggregate losses, of the order of one or two percent of GDP. For business investment plans, this is not helpful. What is needed is a “bottom up” approach, of the sort recommended in the Dore-Burton CCAF Agreement No. A209. Indeed, we suggest that this agreement can be viewed as the first stage in a multi-year plan to generate the required information on the costs of adaptation.

In such a multi-year plan, an obvious priority is the cost of adaptation in areas of government responsibility at all levels, federal, provincial, municipal and other crown agencies. These responsibilities include all social infrastructure such roads, bridges, power stations, transmission lines, ports, airports, ferries, dams). It also includes water utilities, hospitals, and fire stations. This information can be used to make the infrastructure optimally resilient to impacts of climate change. The research on infrastructure should be followed by research on the next priority, which we think should be the health sector, broadly interpreted. The health of Canadians depends on hospitals and the health care delivery system, and a reliable supply of clean water through a reliable water infrastructure. Once the health sector has been covered, attention must be given to the large manufacturing sector, the energy sector and the agricultural sector. All this requires the use of a consistent data collection protocol (DCP), a problem on which the Dore-Burton team is working under CCAF Agreement #A209.

By the end of the first year of the Dore-Burton contract, the DCP will have been pre-tested and applied to:

1. social infrastructure
2. the energy sector
3. the manufacturing sector, at a three-digit NAICS level of aggregation

We can think of the Dore-Burton Agreement as the first year of a five-year research plan. If the sectoral priorities proposed here are plausible, then the research program can be seen as an integrated whole, with common definitions of impact costs, adaptation costs, and projecting the same climate change scenarios. At the end of five years, the objective would be to produce fairly detailed disaggregated costs of adaptation that can operationally be useful to all businesses, government agencies and householders. Thus in five years' time, a new factory, whether in food processing or heavy engineering, would have sectoral (three-digit or five-digit level NAICS disaggregation) benchmarks of adaptation costs that it can use in the design of its buildings, its capital equipment and its output. For example, the output of cars and trucks would be adapted to climate change; they might have exteriors more resilient to hail damage and stronger wipers for heavy downpours of rain. The trucks could be built higher for flash floods.

Similarly, a municipality planning its water infrastructure would be made resilient to climate change; the system might have built-in inventories at the consumer level, better managed reservoirs, pipes that integrate new information technology for monitoring flows, leaks and pathogens, and be better prepared for regional droughts and peak summer loads demands. The cost of water would reflect the adaptation costs incurred. By incurring the adaptation costs, the municipality will protect Canadian households and businesses from the possible consequences of climate change.

Table 3: Synopsis of Five-year Integrated Research Plan

Year 1	1. Definitions of climate change impact costs and adaptation costs. 2. Literature review 3. Formulation of the DCP – pre-tested and used on 3 sectors (a) social infrastructure (b) energy sector (c) manufacturing sector (3 digit-level NAICS disaggregation)
Year 2	1. Refinement and review of DCP 2. Regional disaggregation of the adaptation costs of social infrastructure carried out in Year 1. Regions as defined in the "Canada Country Study" (Environment Canada, 1998). 3. BENCHMARK adaptation costs for social infrastructure 4. Adaptation costs of the health sector, especially hospitals and long-term care facilities

Year 3	1. Regional disaggregation of the adaptation costs of (a) water utilities; (b) electricity utilities. 2. Regional disaggregation of the adaptation costs of the energy sector (oil and gas in particular); Year 1 data to be disaggregated by regions 3. Regional disaggregation of the adaptation costs of agriculture and forestry.
Year 4	1. Disaggregation of the adaptation costs of the manufacturing sector to 5 digit NAICS level (disaggregate Year 1 results)
Year 5	1. Reconciliation of sectoral and regional disaggregations 2. National level adaptation costs 3. Publication of BENCHMARK adaptation costs FOR ALL SECTORS AND REGIONS OF CANADA 4. A stakeholder conference to disseminate the information on benchmarks.

Summary of Part 4:

The review of the literature shows that a consistent methodology for estimating adaptation costs at the micro level does not exist. What does exist is a methodology that regards climate change as a marginal project. This methodology is conceived at a high level of abstraction and four key assumptions need to be relaxed. This can be done systematically, by using a consistent micro level approach and a common DCP, and making the estimates of adaptation dependent on climate change scenarios, "downscaled" for specific local census division levels. At the end of the five years of research, we shall have disaggregated benchmark adaptation costs for all sectors of the Canadian economy. Thus, individual households, private firms and public agencies will have these benchmark costs that they can take into account in order to protect themselves from the adverse impacts of climate change. A well-prepared government is one that has a common template for the estimation of the adaptation costs, and ready information for all stakeholder groups. The work carried out here in Canada can then be offered to other IPCC countries for possible adoption and modifications required for specific countries.

<u>Endnotes</u>

Part 2

1. A preference relation R is homothetic if x^1Rx^2 iff lx^1Rlx^2 for $l>0$.

2. It is well known that this line integral is path independent. For the mathematical theory behind this assertion, see Apostol (1967, pp. 276-293).

3. In the political philosophy literature, this outside imposition of utility maximization is called a "God's Law". Liberals like John Rawls argue that this is in effect "dictatorial" and therefore incompatible with liberalism. Individuals must be free to pursue their own goals, irrespective of what they may be. These goals could include some altruistic activity that is precluded in the (selfish) utility maximization approach. If person A's utility also depends on the utility of person B, then the standard general equilibrium solution is not possible: the two utility functions must be independent of each other. For a further discussion of the issue of God's Law, see Binmore (1994) or Dore and Mount (1999).

References

Introduction

Bromley,D.W. (ed) (1995). *The Handbook of Environmental Economics.* Oxford,UK: Blackwell.

Environment Canada, Adaptation and Impacts Research Group (1998). *Canada Country Study.* Ottawa, ON: Environment Canada.

Fankhauser,S. (1995). *Valuing Climate Change: The Economics of the Greenhouse*. London, UK: Earthscan Publications Limited.

Fankhauser,S. (1997). *The Costs of Adapting to Climate Change*. Working Paper, No.13. Washington, DC: Global Environment Facility.

Smith,J.B., N.Bhatti, G.Mezhulin, R.Benioff, M.Budyko, M.Campos, B.Jallow and F.Rijsberman (eds.) (1996). *Adapting to Climate Change*. New York: Springer-Verlag.

United Nations Environmental Programme (1998). *Mitigations and Adaptation Cost Assessment: Concepts, Methods and Appropriate Use.* Denmark: UNEP Collaborating Centre on Energy and Environment. Risø National Laboratory.

Part 1

Adams,R.M., R.A.Fleming, B.McCarl and C.Rosenzweig (1993). A Reassessment of the Economic Effects of Global Climate Change on US Agriculture. *Climatic Change*, 30, 147-167.

Carter,T.R., M.Parry, H.Harasawa and S.Nishioka (1994). *Intergovernmental Panel on Climate Change Technical Guidelines for Assessing Climate Change Impacts and Adaptations.* London: University College, Department of Geography.

Fankhauser,S. (1995). Protection vs. Retreat. The Economic Costs of Sea Level Rise. *Environment and Planning*, A, 27, 299-319.

Fankhauser,S. (1997). *The Costs of Adapting to Climate Change*. Working Paper, No.13. Washington, DC: Global Environment Facility.

Intergovernmental Panel on Climate Change (1996a). *Climate Change 1995: Impacts Adaptation and Mitigation of Climate Change – Scientific-Technical Analysis. Contribution of WorkingGroup II to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Intergovernmental Panel on Climate Change (1996b) *Climate Change 1995: Economic and Social Dimensions. Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Mendelsohn, R. (2000). Efficient Adaptation to Climate Change. *Climatic Change.* Vol. 45, Nos. 3-4, pp.583-600.

Mendelsohn,R. and J.Neumann (eds.) (1999). *The Impacts of Climate Change on the American Economy*. Cambridge, UK: Cambridge University Press.

OTA Office of Technology Assessment (1993). *Preparing for an Uncertain Climate*. Washington, DC: US Congress.

Ringius,L., T.Downing, M.Hulme, D.Waughray and R.Selrod (1996). *Climate Change in*

Africa – Issues and Challenges in Agriculture and Water for Sustainable Development, Oslo, Norway: Centre for International Climate and Energy Research.

Smit,B. (ed.) (1993). *Adaptation to Climate Variability and Change. Report of the Task Force on Climate Adaptation.* Downsview, ON: Environment Canada. The Canadian Climate Program.

Smith,J.B., N.Bhatti, G.Mezhulin, R.Benioff, M.Budyko, M.Campos, B.Jallow and F.Rijsberman (eds.) (1996). *Adapting to Climate Change*. New York: Springer-Verlag.

Smith,J.B. and S.S.Lenart (1996). Climate change adaptation policy options. *ClimateResearch*, 6, 193-201.

Titus,J.G. (1990). Strategies for Adapting to the Greenhouse Effect. *Journal of the American Planning Association*, 56(3), 311-323.

Titus,J.G., R.A.Park, S.P.Leatherman, J.R.Weggel, M.S.Greene, P.W.Mausel, S.Brown, C.Gaunt, M.Trehan and G.Yohe (1991). Greenhouse Effect and Sea Level Rise: The Cost of Holding Back the Sea. *Coastal Zone Management,* 19, 172-204.

Tol,R., J.Smith and S.Fankhauser (1998). The Scope for Adaptation to Climate Change: What Can We Learn from the Impact Literature? *Global Environmental Change*, 8(2), 109-123.

United Nations Environmental Programme (1998). *Mitigations and Adaptation Cost Assessment: Concepts, Methods and Appropriate Use.* Denmark: UNEP Collaborating Centre on Energy and Environment. Risø National Laboratory.

Yohe,G.W., J.E.Neumann, P.B.Marshall and H.Ameden (1996). The Economic Cost of the Greenhouse Induced Sea Level Rise for Developed Property in the United States. *Climate Change,* 32(4), 387-410.

Part 2

Apostol,T.A. (1967). *Calculus* 2nd Ed. Waltham, MA: Blaisdell Publishing Co.

Arrow,K. and G.Debreu (1954). Existence of Equilibrium for a Competitive Economy. *Econometrica*, 22, 265-290.

Arrow, K.J. and A. Fisher (1974). Preservation, Uncertainty and Irreversibility. *Quarterly Journal of Economics*, 88, 312-319.

Arrow,K. and H.Raynaud, (1986). *Social Choice and Multicriterion Decision-making.* Cambridge, MA: MIT Press.

Ayres,A. and J.Walter (1991). The Greenhouse Effect: Damages, Costs and Abatement. *Environmental and Resource Economics,* 1(3), 237-270.

Azar,C. and Sterner,T. (1996). Discounting and Distributional Considerations in the Context of Global Warming. *Ecological Economics,* 19(2), 169-184.

Bala,V. and N.M.Keefer, (1994). Universally Convergent Mechanisms. *Journal of Economic Dynamics and Control*. 18, 299-316.

Boadway,R.W. (1974). The Welfare Foundations of Cost-benefit Analysis. *Economic Journal*, 84, 426-439.

Binmore,K. (1994). *Game Theory and the Social Contract. Volume 1: Playing Fair*. Cambridge, MA: MIT Press.

Chapman,D., V.Suri, and S.G.Hall, (1995). Rolling DICE for the Future of the Planet. *Contemporary Economic Policy,* 13(3), 1-9.

Chipman,J. and J.Moore, (1980). Compensating Variation, Consumer's Surplus and Welfare.

American Economic Review, 70, 933-949.
Cline,W.R. (1996). The Impact of Global Warming on Agriculture: Comment. *American Economic Review,* 86(5), 1309-1311.
Costanza,R.(ed.) (1991). *Ecological Economics: the Science and Management of Sustainability*. New York: Columbia University Press.
Costanza,R., R.D'Arge, R.de Groot, S.Farber, M.Grasso, B.Hannon, K.Limburegh (1997). The Value of the World's Ecosystem Services and Natural Capital. *Nature,* 387 (6630), 253-260.
Debreu,G. (1974). Excess demand functions. *Journal of Mathematical Economics,* 1, 15-23.
Dore,M.H.I. (1993). *The Macrodynamics of Business Cycles*. Cambridge, MA: Basil Blackwell.
Dore,M.H.I (1997). On Playing Fair: Professor Binmore on Game Theory and the Social Contract, *Theory and Decision,* 43(3), 219-239.
Dore,M.H.I. and T.Mount (eds.) (1999). *Global Environmental Economics*. Maldon, MA: Basil Blackwell.
Duhem,P. (1906). *The Aim and Structure of Physical Theory.* Princeton, NJ: Princeton University Press.
Ekins,P. (1996). The Secondary Benefits of Cost Abatement: How Much Emission Reduction do They Justify? *Ecological Economics,* 16(1), 13-24.
Friedman,M. (1968). The Role of Monetary Policy. *American Economic Review,* 58(1), 1-17.
Gibbard,A. (1973). Manipulation of Voting Schemes: a General Result. *Econometrica,* 41, 587-602.
Hanley,N. and C.L.Spash (1993). *Cost-Benefit Analysis and the Environment.* Aldershot, Hants: Edward Elgar Publishing.
Hanneman,W.M. (1991). WTP and WTA: How Much Do They Differ? *American Economic Review*, 81(3), 635-647.
Henry, C. (1974a). Investment Decisions under Uncertainty: the Irreversibility Effect, *American Economic Review*, 64 (6), 1006-1012.
Henry, C. (1974b). Option Values in the Economics of Irreplaceable Assets, *Review of Economic Studies*, 41, 89-104.
Jepma,C. and M.Munasinghe (1998). *Climate Change Policy: Facts, Issues and Analyses.* Cambridge, UK: Cambridge University Press.
Mantel,R. (1972). On the Characterization of Aggregate Excess Demand. *Journal of Economic Theory*, 7, 348-53.
Maxwell,J.C. (1877). *Matter and Motion*. New York: Dover Publications.
Marschak, T. and R.Nelson (1962). Flexibility, Uncertainty and Economic Theory. *Metroeconomica*, 14, 42-58.
Neumayer,E. (1999). *Weak Versus Strong Sustainability: Exploring the Limits of Two Opposing Paradigms*. Cheltenham and Northampton: Edward Elgar Publishing.
Nordhaus,W.D. (1994). *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: MIT Press.
Nordhaus,W.D. (ed.) (1998). *Economics and Policy Issues in Climate Change* Baltimore; Resources for the Future.
Nordhaus,W.D. and D.Popp. (1997). What is the Value of Scientific Knowledge? An Application to Global Warming Using the PRICE Model. *Energy Journal,* 18(1), 1-45.
Pearce,D.W., A.Markandya, E.Barbier (1989). *Blueprint for a Green Economy*. London, UK: Earthscan Publications Ltd.

Price, M.F. (1995). Climate Change in Mountain Regions: A Marginal Issue? *The Environmentalist,* 15(4), 272-280.
Randall,A. and J.R.Stoll (1980). Consumer's Surplus in Commodity Space. *American Economic Review,* 71, 449-457.
Rawls,J. (1971). *A Theory of Justice*. Cambridge, MA: Harvard University Press.
Saari,D.G. (1985). Iterative Price Dynamics. *Econometrica,* 53, 1117-1131.
Saari,D.G. (1992). The Aggregate Excess Demand Function and Other Aggregation Procedures. *Journal of Economic Theory,* 2, 359-388.
Saari,D.G. and S.Williams (1986). On the Local Convergence of Economic Mechanisms. *Journal of Economic Theory,* 40, 152-167.
Samuelson,P.A. (1947). *Foundations of Economic Analysis*. Cambridge, MA: Harvard University Press. Enlarged edition, 1983.
Satterthwaite,M. (1975). Strategy-proofness and Arrow's Condition: Existence and Correspondence Theorems for Voting Procedures and Social Welfare Functions. *Journal of Economic Theory,* 10, 187-217.
Scarf,H. (1960). Some Examples of Global Instability of the Competitive Equilibrium. *International Economic Review,* 1, 157-172.
Sen,A.K. (1977a). On Weights and Measures: Informational Constraints in Social Welfare Analysis. *Econometrica,* 45, 1539-1572.
Sen,A,K. (1977b). Rational Fools: a Critique of the Behavioural Foundations of Economic Theory. *Philosophy and Public Affairs,* 6, 317-344.
Sen,A.K. (1979a). Personal Utilities and Public Judgments: or What is Wrong with Welfare Economics. *Economic Journal,* 89, 537-558.
Sen,A.K. (1979b). Utilitarianism and Welfarism. *Journal of Philosophy,* 76(9), 463-489.
Sen,A.K. (1984). *Resources, Values and Development.* Oxford, UK: Blackwell
Smale,S. (1976). A Convergent Process of Price Adjustment and Global Newton Methods. *Journal of Mathematical Economics*, 3, 107-120.
Sonnenschein,H. (1973). Do Walras' Identity and Continuity Characterize the Class of Community Excess Demand Functions? *Journal of Economic Theory,* 6, 345-354.
Tol,R.S.J. (1994). Communication-the Damage Costs of Climate Change: a Note on Tangibles and Intangibles, Applied to DICE. *Energy Policy,* 22(5), 436-438.

Part 3

Agriculture and Agri-food Canada, *Federal-Provincial-Territorial Communique*. Accessed on 8/3/00 htttp://www.agr.ca/cb/news/2000/n00705be.html.
Agriculture and Agri-food Canada, *Minister's Statement*. Accessed on 8/3/00, http://www.agr.ca/cb/news/2000/n00705ce.html.
Agriculture and Agri-food Canada, Research Branch, *Business Plan*. Accessed on 8/3/00, http://res2.agr.ca/research-recherche/business/resbplan/
Agricultural Research Institute of Ontario, Ministry of Agriculture, Food and Rural Affairs, Accessed on 8/3/00, http://www.gov.on.ca:80/OMAFRA/english/research/ario/ariobudget.html.
Brun,S.E., D.Gesink,L.Wallace, D.Etkin and R.White (eds.) (1997). *Coping with Natural*

Hazards in Canada: Scientific, Government and Insurance Industry Perspectives. Round Table on Environmental Risk, Natural Hazards and the Insurance Industry. Toronto: Insurers Advisory Organization Inc.

Burton,I., M.Kerry, S.Kalhok and M.Vandierendonck. (1999). *Report from the Adaptation Learning Experiment*. Toronto: Environment Canada and Emergency Preparedness Canada.

Darwin,R., M.Tsigas, J.Lewandrowski and A.Raneses (1995). *World agriculture and climate change: economic adaptations, Agricultural Economic Report No.703*,Washington, D.C.: Department of Agriculture.

Department of the Environment, Transport and Regions (2000). *The Potential Adaptation Strategies for Climate Change, Report 99DPL013.* London, UK: Environmental Resources Management

Easterling,W.E., P.R.Crosson, N.J.Rosenberg, M.S.McKenney, L.A.Katz and K.M.Lemon (1993). Agricultural Impacts and Responses to Climate Change in the Missouri-Iowa-Nebraska-Kansas (MINK) Region. *Climate Change,* 2, 19-44.

Environment Canada, Adaptation and Impacts Research Group (1998). *Canada Country Study.* Ottawa, ON: Environment Canada.

Etkin,D and J.McColloch (eds.)(1994) *Improving Responses to Atmospheric Extremes: The Role of Insurance and Compensation*. Toronto, ON: Workshop proceedings.

Fankhauser,S. (1995). *Valuing Climate Change: The Economics of the Greenhouse.*London, UK: Earthscan Publications Ltd.

Herbert,D. and I.Burton (1994). Estimated Costs of Adaptation to Canada's Current Climate and Trends Under Climate Change. Downsview, ON: Environmental Adaptation Research Group, Environment Canada.

Intergovernmental Panel on Climate Change (1996)*. Climate Change 1995: Economic and Social Dimensions of Climate Change. The Contribution of Working Group III to the Second Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Jepma,C. and M.Munasinghe (1998). *Climate Change Policy: Facts,Issues, and Analyses.* Cambridge, UK: Cambridge University Press.

Kloeppel,J.E. (1997). *Climate Shift Would Aid Industrial Nations, Hurt Less-Developed Ones*. Urbana-Champaign: University of Illinois News Bureau.

McKenzie Hedger,M., I.Brown, R.Connell and M.Gawith (2000). *Climate Change: Assessing the Impacts – Identifying Responses*. London, UK: Department of the Environment, Transport and Regions, UK Climate Impacts Programme.

Mendelsohn,R., W.D.Nordhaus and D.Shaw (1994). The Impact of Global Warming on Agriculture: A Ricardian Analysis. *American Economic Review,* 84, 753-771.

Mendelsohn, R., (2000). Efficient Adaptation to Climate Change. *Climatic Change,* 45, 583-600.

Mendelsohn,R., W.Morrison, M.E.Schlesinger and N.A.Andronova (2000). Country-Specific Market Impacts of Climate Change. *Climatic Change,* 45(3-4), 553-569.

Mendelsohn,R. and J.Neumann (eds.) (1999). *The Impacts of Climate Change on the American Economy*. Cambridge, UK: Cambridge University Press.

Pearce,D.W. (1997), Economists and Climate Change. *Environment & Planning A*, 28(1),1-4.

Rayner,S. and E.L.Malone (eds.) (1998). *Human Choice and Climate Change Vol.3 The Tools for Policy Analysis*. Columbus: Battelle Press.

Reilly, J., N.Hohmann and S.Kane (1994). Climate Change and Agricultural Trade: Who Benefits, Who Loses? *Global Environmental Change,* 4(1), 24-36.
Rosenzweig,C. and M.L.Parry (1994). Potential Impact of Climate Change on World Food Supply. *Nature,* 367, 133-138.
Smith,J. and D.Tirpak (eds.) (1990). *The Potential Effects of Global Climate Change on the United States.* New York: Hemisphere Publishing Company.
Smith,J.B., N.Bhatti, G.Mezhulin, R.Benioff, M.Budyko, M.Campos, B.Jallow and F.Rijsberman (eds.) (1996). *Adapting to Climate Change*. New York: Springer-Verlag.
Stennes,B., E.Krcmar-Nozic and G.Vornelis van Kooten (1998). Climate Change and Forestry: What Policy for Canada? *Canadian Public Policy,* 24, Supplement 2.
Strzepek,K. and J.Smith (eds.) (1995). *As Climate Changes:International Impacts and Implications.* Cambridge, UK: Cambridge University Press.
Tol,R.S.J. (1995). The Damage Costs of Climate Change: Toward More Comprehensive Calculations. *Environmental and Resource Economics,* 5, 353-374.
Tol,R.S.J. (1996a). *A Decision-Analytic Treatise of the Enhanced Greenhouse Effect.* Ph.D. dissertation, Institute for Environmental Studies, Amsterdam: Vrije Universiteit.
Tol,R.S.J. (1996b). The Damage Costs of Climate Change Towards a Dynamic Representation. *Ecological Economics,* 19, 67-90.
Tol,R.S.J. (1999a). *New Estimates of the Damage Costs of Climate Change. Part I:Benchmark Estimates.* report D99/01. Institute for Environmental Studies, Amsterdam: Vrije Universiteit.
Tol,R.S.J. (1999b). *New Estimates of the Damage Costs of Climate Change. Part II:Dynamic Estimates.* report D99/02. Institute for Environmental Studies, Amsterdam. Vrije Universiteit.
US Congress, Office of Technology Assessment (1993). *Preparing for an Uncertain Climate-Volume I.* OTA-0-568, Washington DC: US Government Printing Office.
Zeidlar,R. (1997). Climate Change Vulnerability and Response Strategies for the Coastal Zone of Poland. *Climatic Change,* 36: 151-173

Part 4

Dore,M.I.H. and D.Etkin (forthcoming). A Consistent Methodology for Estimating the Economic *Costs of Natural Disasters: With the 1998 Ice Storm as a Case Study*. Toronto: University of Toronto Press.
Dore,M.I.H. and I.Burton (forthcoming) Valuing Environmental Degradation and Costing Remediation: Is Economics Part of the Problem? Journal of Environmental Monitoring and Assessment.