PROTECTION VS. RETREAT: ESTIMATING THE COSTS OF SEA LEVEL RISE

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CSERGE Working Paper GEC 94-02

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Acknowledgements:

The Centre for Social and Economic Research on the Global Environment (CSERGE) is a designated research centre of the U.K. Economic and Social Research Council (ESRC).

I am grateful to Snorre Kverndokk, David Pearce, Kerry Turner and David Ulph for comments on an earlier version of the paper.

ISSN 0967-8875

Abstract

This paper analyses the relative role of protection and mitigation expenditures within the total costs of climate change induced sea level rise. It derives a rule of thumb to approximate the optimal level of protection. Economic efficiency requires that protection expenditures are designed such that the sum of protection costs plus remaining land loss damage is minimised. A formula is derived according to which the optimal protection level depends on the relative importance of dryland loss compared to the costs of accelerated wetland loss plus protection expenditures. This framework is then used to estimate sea level rise damage cost functions for the countries of the OECD.

1. INTRODUCTION

In this paper we sketch out the damage costs from a climate induced increase in sea level. The case of sea level rise (SLR) is of interest for at least two reasons. First, SLR appears to be one of the most important and harmful impacts of global warming. Existing estimates suggest that SLR related costs may account for 10 to 20% of total greenhouse damage, more than most other damage categories (see Cline, 1992a; Nordhaus, 1991; Fankhauser, 1993; 1992). Second, SLR well illustrates the fact that parts of greenhouse costs will not actually be damage costs as such, but will arise from the implementation of damage mitigation strategies, such as the erection or modification of sea defences.

A first concern of the paper is thus the question of the optimal degree of SLR damage mitigation. In general, mitigation should take place as long as the benefits from avoided damage exceed the incremental costs of additional action. In the case of SLR the trade off is between the costs of protection on the one side, and the value of the land at threat on the other, but it should also take into account that protection walls lead to a reduction in the damage from storm surges, while on the other hand they accelerate the loss of valuable wetlands by inhibiting them from migrating inland.

Most damage studies do not explicitly model this trade off and instead assume an exogenously given rule about the optimal level of protection, usually a partial retreat scenario in which highly developed areas are protected, while sparsely populated or low value land is abandoned (see e.g. IPCC, 1990). While this seems a reasonable rule of thumb, there is no guarantee that it will hold in general. The optimal degree of protection may differ between regions as well as for different degrees of SLR. For example, we may find lower optimal protection levels in poorer countries, where the costs of protection may be relatively high compared to the value of land at threat[1]. At first sight we may also expect that a high SLR will lead to a higher degree of protection, since a larger part of the hinterland is now at threat and the potential land loss damage is higher. But then, mitigation costs per kilometre of coast will also increase, since higher protection measures are now required, and this would point towards a lower degree of protection. The net effect here thus seems unclear. To shed further light on such aspects, the optimal degree of protection is determined endogenously in this paper.

[1] It is often, and correctly, pointed out that poor countries may lack the funding to implement sufficient protection measures and, as a consequence, will be underprotected. Note that this is not the point made here. Here we argue that

The second concern of the paper is with an overall assessment of SLR damage. Designing the optimal policy response to SLR is mainly a problem of regional coastal zone management, and the optimal protection strategy will generally be different for different coastlines. Ideally the global picture would thus emerge from the aggregation of the many existing local assessments (see e.g. Turner *et al.*, 1994, on East Anglia; Gleick and Maurer, 1990, on the San Francisco Bay; Milliman *et al.*, 1989, on the Nile and Bengal deltas; den Elzen and Rotmans, 1992, and Rijkswaterstaat, 1991 on the Netherlands; IPCC, 1992b, on several regions). However, it is evidently not feasible to study all vulnerable coastlines in the required detail, and a global assessment of SLR damage will therefore necessarily have to be based on a "top down" approximation[2]. Several attempts to such a "top down" assessment have already been made, e.g. IPCC (1990, 1992b), Rijsberman (1991), Titus *et al.* (1991). These studies typically concentrate on just one or two scenarios, e.g. on the benchmark case of a 1 metre rise by the year 2100. The present paper goes further in that it provides an entire SLR damage function. The paper also explicitly pays attention to the gradual character of SLR, which will occur slowly over time.

The structure of the paper is as follows. Section 2 provides a general outline of the role of damage, mitigation and abatement costs within a cost-benefit framework. The special case of SLR is then analysed in the subsequent sections. In section 3 we set up a model of optimal SLR mitigation, as seen from the point of view of coastal zone managers. The model is solved in section 4, which also derives a simple formula for calculating the optimal mitigation strategy. Section 5 turns the attention to applied aspects, and contains illustrative cost estimates of SLR damage for the countries of the OECD. Conclusions are drawn in section 6.

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even if funds were available it would not be efficient to achieve the same degree of protection as in a rich country.

[2] The ongoing attempts to derive a global picture from local case studies are summarised in IPCC (1992b).

2. GREENHOUSE GAS ABATEMENT vs. DAMAGE MITIGATION: THE GENERAL CONTEXT

Loosely, policy makers have two sets of options to moderate the impacts of greenhouse warming. They can either limit the amount of greenhouse gases emitted - the well known abatement option, leading to a lower degree of warming - or, they can ease the impacts of a given change through appropriate protection/adaptation measures. Although we will concentrate on the example of SLR here, mitigation is in no way limited to SLR protection. Mitigation activities may for example include the development of heat resistant crops, a change in forest management, the construction of water storage and irrigation systems, the adaptation of houses, and the like. Both sets of options, abatement and mitigation, have to be taken into account when drafting the greenhouse policy response. Analytically, the optimal combination of abatement and mitigation can be found by minimising the total costs of climate change, consisting of the costs of emissions abatement AC[3], the costs of mitigation measures P and the costs of greenhouse damage D, i.e.

$$\min_{m,e} \quad AC(e)+P(m)+D(T,m) \qquad \textbf{(1)}$$

subject to

$$T=f(e) \qquad \textbf{(2)}$$

where e denotes the level of abatement, and m the degree of mitigation. Climate change is symbolised by the variable T (for temperature change), and depends negatively on the amount of abatement e, $f' < 0$. The higher the abatement effort, the lower the temperature increase. Further we have AC', P', $D_T > 0$ and $D_m < 0$. All functions are assumed to be convex so that first order conditions are both necessary and sufficient for an optimum.

The optimal abatement and protection levels e^* and m^* are then determined by the two first order conditions

$$\text{a)} \quad AC' = D_T f'$$
$$\text{b)} \quad P' = -D_m \qquad \textbf{(3)}$$

[3] Climate change prevention policies may also include geo-engineering. We abstract from this option here.

Marginal abatement costs (AC') and marginal mitigation costs (P') equal the marginal benefits from increased abatement ($-D_T f'$) and mitigation ($-D_m$), respectively. The point to note is that the optimal value for each of the options, e^* and m^*, depends on the value chosen for the other. Consequently, e^* and m^* should in principle be determined simultaneously.

In the real world this is hardly ever the case. Decisions about e^* and m^* are usually taken at different political levels. The question of optimal emissions is in general addressed globally, in international negotiations between countries or at international conferences such as UNCED 1992. The composition of optimal mitigation strategies, on the other hand, is often left to local authorities, in the case of coastal protection for example to the regional coastal zone managers. The same division is also reflected in the literature, where studies typically either deal with the optimal abatement question (Nordhaus, 1991, 1992, 1993; Peck and Teisberg, 1992; Cline, 1992a and b; Tahvonen, 1993) or with the optimal level of mitigation, usually in the context of sea level rise protection (e.g. Turner *et al.*, 1994; Gleick and Maurer, 1990). The following analysis will show that this two step process of decision making will lead to the same result as a simultaneous optimisation, provided that the damage function in the second, global, step is appropriately defined.

To analyse the local problem of optimal mitigation then, it is easiest to interpret regions as *climate takers*. The greenhouse gas emissions of an individual region or country are in most cases so small that they have virtually no influence on world climate (Adger and Fankhauser, 1993). Climate, and climate change, is therefore exogenously given, and the regional decision problem is merely concerned with finding the optimal degree of protection against this change,

$$\min_m \quad P(m)+D(m½T=f(e)) \qquad \textbf{(4)}$$

Again the first order condition will require that marginal protection costs (P') equal the marginal benefit from damage avoided ($-D_m$). Because D_m is a function of the exogenous climate change, the optimal mitigation level will also be a function of T, and thus ultimately of e, $m^* = m(T)$, with $T = f(e)$.

We can now define a function

$$V(T) = \min_m[P(m) + D(m|T)]$$
$$= P[m^*(T)] + D[m^*(T),T] \quad \textbf{(5)}$$

V(T) denotes the combined mitigation and damage costs of climate change caused by a level of change T, given that the optimal policy response has been taken with respect to mitigation. Note that V(T) is also a convex function[4].

Let us now turn to the global problem of optimal abatement. Intuitively it should be clear that it is this function V, or its aggregation over all regions, which is relevant to the global problem and that the correct way of deciding the optimal abatement level is to trade off the costs of abatement AC with the minimal combined damage costs V. That is, the global problem is

$$min_e \quad AC(e) + V(T) \quad \textbf{(6)}$$

where again T=f(e). It is easily shown that problem (6) indeed yields the same solution as problem (1), i.e. that its solution is described by the optimal conditions (3). From the definition of V we know that condition (3b) will always hold. Optimisation of (6) yields the first order condition

$$AC' = -V'f' = -D_T(m^*)f' \quad \textbf{(7)}$$

where the second equality follows from the envelope theorem[5]. Condition (3a) is thus also satisfied. The two step process in which mitigation decisions are taken locally, while the optimal abatement level is determined at a global level thus provides the same solution as a simultaneous optimisation. There is nothing terribly new about this finding. The analysis was mainly carried out to underline a different point, which is the characteristic of the global warming damage function as a minimum function like V(T).

Most damage studies acknowledge this property or at least pay lip service to it. However, when

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[4] If f(x, a) is convex in (x, a) then F(a) = $\max_x$ f(x, a) is convex in a (Mangasarian and Rosen, 1964).

[5] The envelope theorem states that, if F(a) = $\max_x$ f(x, a), then

$$\frac{dF}{da} = \frac{\partial f(\bullet)}{\partial a}\Bigg|_{x=x^*}$$ **Error! Main Document Only.**

where x^* denotes the choice for x which maximises f(.) (see e.g. Varian, 1984).

it comes to actual damage calculations, data limitations do not always allow its careful implementation. The failure to capture managerial responses in most of the agricultural damage literature may serve as a prime example here (for an exception see e.g. Easterling *et al.*, 1993). In the remainder of this paper we attempt to derive a minimum function like V(T) for SLR. To do this we first analyse the local problem of optimal mitigation for the case of SLR.

3. A MODEL OF OPTIMAL SEA LEVEL RISE MITIGATION

3.1 General Description

Finding the optimal SLR mitigation strategy is not as easy as may have been suggested in the previous section. Instead of the single and continuous variable m decision makers will be confronted with a host of alternative strategies. In its 1990 report the coastal zone management subgroup of the IPCC divided available SLR response options into three groups, with the following definitions (IPCC, 1992b, p.8; see also IPCC, 1990):

> "*Retreat* - abandon structures in currently developed areas, resettle the inhabitants, and require that any new development be set back specific distances from the shore, as appropriate".

> "*Accommodate* - continue to occupy vulnerable areas, but accept the greater degree of flooding (e.g convert farms to fish ponds)".

> "*Protect* - defend vulnerable areas, especially population centres, economic activities, and natural resources".

In addition, authorities will be confronted with a multitude of protection options, including beach nourishment, island rising and the building of dams, dikes and sea walls. Several simplifying assumptions had thus to be introduced to make the problem tractable.

As a major simplification the model abstracts from the "accommodate" option. That is, coastlines are either protected, or, if this is not done, they will eventually have to be abandoned and will be lost to the rising sea. We assume that only one protection measure is available per region, or, which is equivalent, that the same measure is cost-effective throughout a region[6]. For illustrative purposes we can think of the optimal measure as a sea wall.

Two kinds of land are distinguished, dryland and wetland, and we assume that coasts are protected in accordance to their dryland value, i.e. more valuable dryland is protected first. Wetlands, on the other hand, cannot be protected directly. There is nevertheless an indirect link to the amount of coastal protection, in that the ability of wetlands to adjust and migrate inland

[6] To allow for different measures within a region, e.g. for different types of coastline, we could further subdivide a region according to coastal types, e.g. into beaches, open coastlines, etc. The same analysis would then have to be carried

will be reduced by the existence of obstacles such as a sea wall. The loss in wetlands is therefore inversely related to the degree of coastal protection. The more comprehensive the defence measures, the more coastal wetlands will be lost. For lack of data we abstract from the impacts of salt water intrusion and the costs of increased storm and flood damage. We also assume that the amount of SLR is known with certainty (for a treatment of uncertainty see Yohe, 1991).

The main problem faced by policy makers is then to determine the proportion of coastlines worth protecting. Their decision variable is L, $0 \leq L \leq 1$, the percentage of coastlines protected. SLR will occur gradually over time. Local authorities are therefore faced with a second problem, which is to find the optimal intertemporal protection path, i.e. with the question of when a sea wall should optimally be build. This problem will be of less interest here, and, given our model assumptions, the optimal construction path will follow trivially. A more detailed analysis of this problem can be found in den Elzen and Rotmans (1992).

The costs of sea level rise in each year thus consist of three elements, protection costs, dryland loss and wetland loss. In the following three subsection they are analysed in more detail, before we come back to the total picture in section 3.5.

3.2 Protection Costs

Although there are no studies which provide an entire protection cost function, it follows from existing estimates (IPCC, 1990, Titus *et al.*, 1991) that costs may rise exponentially with height, but will be linear in the length of coastline protected. The protection cost function may therefore be of the form

$$C(G,L) = LK \cdot \varphi G^{\gamma} \qquad \textbf{(8)}$$

where K denotes the length of threatened coastline[7], and LK therefore the length of coastlines protected. G is the height of the defence measure. γ and _ are two cost parameters. Note that the expression does not contain a fixed cost term, clearly a simplifying assumption.

Expression (8) gives the total (undiscounted) costs of protection, that would occur if measures of height G were installed at once. However, if sea level is rising only gradually over time, the full

out for each of them. This will be the method used in section 5.

[7] Loosely, K denotes the length of coasts not protected by hard rock cliffs.

height G may not be needed immediately, and construction may be spread over several periods. What we are therefore interested in is a stream of annual costs, PC. PC is represented by the following formulation

$$PC(L, h_t, G_\tau) = LK \cdot \varphi \cdot G_\tau^{\gamma-1} \cdot h_t \tag{9}$$

where h_t denotes the change in sea wall height obtained at time t, and G_τ its final height. We thus require ${}_0\int^\tau h_t = G_\tau$. Also note that $PC(L,G_\tau,G_\tau) = C(G_\tau,L)$, i.e. if the wall is built at once annual and total costs coincide. Underlying expression (9) is the assumption that "a brick is a brick". Equation (8) is exponential basically because a higher sea wall will, for stability reasons, also have to be more massive. However, once the final height of the wall is determined, it makes no difference whether an additional layer of bricks is added today or tomorrow, as long as we abstract from discounting effects. Recall that for simplicity we neglect fixed costs (e.g. hiring and firing costs).

Note that we assume protection costs not to rise over time. To the extent that the economy is growing, the costs of protection relative to GNP will therefore fall over time.

3.3 Dryland Loss

SLR damage from dryland loss depends on two aspects: on the amount of land lost and on its value. For the former we specify a linear relationship with SLR and length of coast, and assume that a land area of ψ will be lost per cm of SLR and km of coastline. The situation is depicted in Figure 1 which also shows the connection between ψ and the slope of the coastline[8]. Given that a fraction L of all coastlines will be protected, a SLR of S will inundate an area of $(1\text{-}L)K\psi S_t$. To get the monetary damage this value has to be multiplied by the annual return on land, R_t. R_t is the opportunity cost of lost land, i.e. it denotes the return the lost area would have yielded in period t, had it not been inundated. The dryland loss at time t is therefore

$$DL_t(L,S_t) = (1\text{-}L)K \cdot \psi S_t \cdot R_t(L) \tag{10}$$

The return on land, R_t, is simply the value of lost land multiplied by the rate of return on capital π. It is specified as a function of L. Since more valuable areas will by assumption be protected

[8] Note that, strictly, the linearity assumption only applies to flat coasts. In the special case of soft rock cliffs, which are threatened from increased erosion, the underlying processes are more complex than shown in Figure 1. In most cases, though, soft cliffs are preceded by beaches (created through previous erosion) for which the linearity assumption holds.

with priority, the average return on unprotected land, R_t, will decrease with increasing protection efforts. By increasing protection, we truncate the top end of the value distribution for unprotected land, and the mean will therefore decrease. The situation is depicted in Figure 2. For simplicity we assume a uniform distribution for the value of dryland, with an expected value of x_t and a minimum value of zero[9]. As is shown in Figure 2 this implies a linear relationship between R_t and L, as follows,

$$R_t(L) = \pi \cdot x_t(1-L) \qquad \textbf{(11)}$$

For L=0, i.e. if no protection takes place, the average value of unprotected coasts equals the overall expected value for land, x_t, and the annual return is consequently πx_t. As L increases the value of unprotected areas decreases and approaches zero for the last unprotected coastal strip. Note that we do not assume changes in π over time. The value of land on the other hand will increase over time as the economy grows and land becomes more scarce relative to income. We assume a proportional relationship

$$x_t = x_0 e^{gt} \qquad \textbf{(12)}$$

where g is the exogenously given rate of economic growth. Note that x_t does not depend on the amount of land lost. The underlying assumption is that land losses will be too marginal to affect prices. For large countries, or those with short coastlines this seems reasonable. For extremely small countries it may lead to an underestimation of true damage.

3.4 Wetland Loss

SLR will increase the already existing pressure on coastal wetland areas. As with many ecosystems, it is not so much the absolute level of climate change (or SLR) as the rate of change which poses a threat. Wetlands are in principle able to adjust to SLR by migrating inland, but may be too slow if the rate of SLR is too high. In addition, backward migration is only possible if there are no obstacles in the way, and it may therefore be limited to unprotected areas.

SLR induced wetland losses can therefore be expressed as follows. Suppose wetlands are able

[9] In principle x_t should cover both market and non-market aspects. The simulations below will however be based on market values alone.

to migrate at a speed of α, but only along the unprotected coast. At time t coastal wetlands will have migrated by αt and will have grown by an area of W(1-L)αt, where W denotes the length of coastal wetlands[10]. At the same time, however, some land will have been lost through inundation. The expression for this latter part can be taken from equation (10) above. Wetland loss is thus defined as[11]

$$WL_t(L,S_t) = [\psi S_t - (1-L)\alpha t]W \cdot R_t^W \tag{13}$$

Note that, as opposed to the dryland case, the return on wetlands, R^W, does not depend on the degree of protection. To see why, remember that the relationship outlined in equation (11) was driven by the assumption that high value dryland will be protected first. If an additional coastline is protected, we know that the land secured is the area worth most, and that the average value of remaining zones will thus decrease. No similar assumption holds for wetlands, which are affected only indirectly. Assuming that there is no correlation between dryland and wetland values, the expected value of the affected wetlands is therefore equal to the mean value of coastal wetlands, x_t^w. Similarly, the expected value of remaining wetlands is x_t^w as well. Again we assume that land values rise in proportion to economic growth. Hence

$$R_t^W = \pi x_0^W \cdot e^{gt} \tag{14}$$

3.5 The SLR Protection Problem

We are now in a position to derive a formulation for the local problem of optimal SLR protection. To recapitulate: For each region (or type of coast) considered, the costs of SLR consist of the three cost elements protection cost, dryland loss and wetland loss, and we seek to minimise the present value of these three cost streams over time. Costs are minimised with respect to the percentage of coasts protected, denoted by the variable L, $0 \le L \le 1$. A second decision variable is the additional height added to the protection measures in each period, h_t. The problem is thus a combination of a static optimisation (with respect to variable L), and a dynamic optimisation (in the case of h_t). It can be expressed as follows

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[10] Strictly, W denotes the length of *marsh wetlands*. Freshwater wetlands such as e.g. the Norfolk Broads cannot migrate and will be lost. We can think of the loss of freshwater wetlands as being included in dryland loss.

[11] Note that the rate of inland migration cannot exceed the rate of inundation (wetlands do not expand into dryland areas). Neither can the wetland loss exceed the total amount of wetlands. Equation (13) thus only holds for $0 \le (\psi S_t - \alpha t) \le 1$. The condition will hold for all the numerical specifications we consider below.

$$\min_{L,h_t} Z = \int_0^{\tau} [PC(L,h_t,G_\tau) + DL_t(L,S_t) + WL_t(L,S_t)]e^{-rt}dt \qquad \textbf{(15)}$$

subject to

$$\begin{aligned} &\dot{G}_t = h_t \\ &G_t \geq S_t \\ &h_t \geq 0 \\ &0 \leq L \leq 1 \\ &G_0 \, given, G_\tau \, free \end{aligned} \qquad \textbf{(16)}$$

with PC, DL_t and WL_t as defined in equations (8) to (14). S_t is the exogenously given SLR path. The requirement $G_t \geq S_t$ reflects the fact that for the sea wall to be effective it has to be at least as high as the sea level[12].

It may be worthwhile to underline again the difference in the decision variables L and h_t. The length of protection, L, is a static variable which is determined at the outset and remains constant thereafter, while the value of h_t, on the other hand, may vary from period to period. For example, if a certain coastline is not threatened immediately, but will be towards the end of the time horizon, the general decision of whether or not to protect it will have to be taken at the outset. The erection of measures, however, may then be delayed until later, i.e. h_t will take values greater than zero only at the end of the time horizon. We will later see that, while the optimal value for L, L^*, depends on h_t, h_t^* does not depend on L.

[12] In a model allowing for storm surges, i.e. where S_t fluctuates over time, the optimal height would be determined in a trade off between the costs of construction and the expected benefits of flooding damage avoided, calculated as the damage per flood event times the probability of occurrence. In the present formulation S_t is known with certainty, whence we can simply impose $G_t \geq S_t$.

4. SOLVING THE MODEL

4.1 The Optimal Height of Protection Measures

Section 3 described the problem of optimal protection faced by local coastal zone managers. In this section we will attempt to find a solution for the two decision parameters L and h_t. This then forms the basis for defining the sea level rise cost function at the end of the section.

Let us start with the intertemporal decision variable h_t. Given the assumptions of our model, the optimisation with respect to h_t is fairly straightforward. h_t and G_t only occur in the expression on protection costs, PC. The question is thus merely how to raise the sea wall at minimum costs without violating the constraints. In principle, the lower the height of the wall, the better. However, in the terminal period the state space constraint will require $G_T \geq S_T$. Since less height is better it will be strictly binding, $G_T = S_T$. Increasing the wall height further would only raise costs without incurring benefits. The ultimate height of the wall is thus set by the amount of SLR expected in the terminal period. This leaves the question of the optimal timing of construction work. In the absence of fixed costs, and under the assumption that "a brick is a brick", which characterises equation (9), construction tomorrow is a perfect substitute for construction today, i.e. there are no gains connected with a one-off erection of measures (see section 3.2). The discounting effect will therefore see to it that construction is carried out as late as possible, constrained only by the requirement $G_t \geq S_t$.

The optimal strategy with respect to the height of defence measures will therefore be not to raise the installations as long as they are higher than the current sea level or if the sea level is falling, and to increase them at the same pace as the sea is rising otherwise. Rising defence structures in earlier periods in anticipation of a future SLR would be inefficient. Or, in formal notation[13]

$$h* = \begin{cases} 0 if S_t \leq G \\ \dot{S}_t otherwise \end{cases} \tag{17}$$

where $\dot{S}_t$ denotes the rate of SLR. Note that the optimal strategy for h_t does not depend on the value of the other decision variable, L.

[13] The same result could also be obtained using control theory. Because of the linearity of the Hamiltonian in the control

This result is mainly an artefact of the simple protection cost formulation (9). In reality sea walls may be altered less frequently than implied by the model, due to fixed costs. The occurrence of storm surges, i.e. the possibility that the sea level may fluctuate and occasionally rise above its trend level S_t, may give rise to a further increase in the height of sea walls[14]. However, for our purpose the gradual representation ignoring storms and fixed costs will suffice[15]. The concern in this paper is less about the optimal height of protection measures than about the optimal degree of protection and the overall costs of SLR. To these aspects we turn next.

4.2 The Optimal Length of Coastal Protection

With respect to variable L, the proportion of coastlines to be protected, the dynamic character of the optimisation problem is of no relevance. To simplify the notation we therefore introduce four variables, which will help to transform the dynamic problem (15) into its static equivalent.

First we define a variable PC^{pv}, which denotes the present value protection costs under the assumption that all coasts are defended, i.e. for L=1. The annual protection expenditures were derived in section 3.2. The corresponding present value is then (from equations (9) and (15))

$$\begin{aligned} PC^{pv}(h_t, G_\tau) &= \int_0^\tau PC(1, h_t, G_\tau) e^{-rt} dt \\ &= K\varphi G_\tau^{\gamma-1} \int_0^\tau e^{-rt} \cdot h_t dt \end{aligned} \tag{18}$$

Similarly, we can introduce a variable DL^{pv} which denotes the present value of dryland loss damage if no coasts were protected at all, i.e. if L=0.

$$\begin{aligned} DL^{pv}(h_t, G_\tau) &= \int_0^\tau DL_t(0, S_t) e^{-rt} dt \\ &= K\psi\pi x_0 \int_0^\tau S_t e^{(g-r)t} dt \end{aligned} \tag{19}$$

variable, the optimal control would yield a bang bang solution and h_t would be set at its lower bound value.

[14] For a more detailed analysis of flood probabilities, security and the optimal height of defence measures, see e.g. den Elzen and Rotmans (1992).

[15] As a sensitivity test the simulations have been run assuming an immediate build up of defence measures, i.e. using equation (8) rather than (9). The results deviated only slightly from those reported here.

The impact on wetlands is split in two parts. We define WG^{pv} as the present value gain from the inland migration of wetlands under L=0, i.e. if full backward migration is possible. Alternatively, WG^{pv} can be interpreted as the forgone gain in wetland growth under full protection. Secondly, WL^{pv} is defined as the present value damage from wetland loss. The net (present value) damage from wetlands under no protection is then

$$WL^{pv}(S_t) - WG^{pv} = \int_0^{\tau} WL(0, S_t) e^{-rt} dt \tag{20}$$

From section 3.4 we derive

$$WG^{pv} = Wa\pi x_0^W \int_0^{\tau} te^{(g-r)t} dt \tag{21}$$

$$WL^{pv}(S_t) = W\psi\pi x_0^W \int_0^{\tau} S_t e^{(g-r)t} dt \tag{22}$$

Using the definitions (18) to (22) equation (15) now reduces to

$$\min_{L,h_t} Z = \left[L \cdot PC^{pv} + (1\text{-}L)^2 DL^{pv} + WL^{pv} \text{-} (1\text{-}L)\, WG^{pv} \right] \tag{23}$$

subject to (16). The equivalence of (23) and (15) can easily be checked by substituting equations (18) to (22) into (15). The dynamic aspects from the second decision variable h_t are now all incorporated in PC^{pv}, the only variable depending on h_t. To derive the optimal value for L we assume that h_t is set at its optimal level, i.e. $h_t = h_t^*$. Notice that since h_t^* does not depend on L, i.e. $\partial h_t^*/\partial L = 0$, we need not worry about indirect effects.

The expression for the optimal solution of L is then easily derived as

$$L^{opt} = 1 - \frac{1}{2}\left(\frac{PC^{pv} + WG^{pv}}{DL^{pv}} \right) \tag{24}$$

Finally, we have to remember that L is bounded from below and above. The upper bound condition, $L^{opt} \leq 1$, presents no problem. It will never be violated as long as the three present value terms are positive. To secure the lower bound condition, $L^{opt} \geq 0$, we rewrite the optimal solution as

$$L^* = \begin{cases} 0 \; if L^{opt} < 0 \\ L^{opt} \; otherwise \end{cases} \qquad \textbf{(25)}$$

The interpretation of equation (24) is straightforward. The numerator of the term in brackets denotes the present value costs under full protection. They consist of the costs of raising the protection wall (PC^{pv}) plus the opportunity costs of forgone wetland gains (WG^{pv}). There is no dryland loss, since protection is complete. Conversely, the denominator represents the present value costs in the absence of any protection measures, consisting solely of land loss damage (DL^{pv})[16].

The optimal level of protection is therefore determined by the relative size of the costs of full protection compared to those under full retreat. The lower the costs of full protection, the larger will be the share of protected coasts. On the other hand, if the (present value) damage from dryland loss is only modest, the degree of protection will be low. We get a corner solution if the costs of full protection are more than twice as high as the costs under full retreat.

4.3 Costs as a Function of Sea Level

We are now in a position to define a cost function for the damage from sea level rise. As explained in section 2, we seek the cost minimising combination of mitigation costs (protection costs) and damage *per se* (dry- and wetland loss). That is, the costs of SLR, denoted as $V(S_t)$, correspond to the minimal value for Z resulting from the optimisation problem described in section 3 and solved above. We get $V(S_t)$ by substituting the optimal values L^* and h_t^* back into problem (23).

$$V(S_t) = L^* PC^{pv}(h_t^*, G_\tau) + (1\text{-}L^*)^2 DL^{pv}(S_t) + WL^{pv}(S_t) \text{-} (1\text{-}L^*) WG^{pv} \qquad \textbf{(26)}$$

Where L^*, h_t^*, PC^{pv}, DL^{pv}, WL^{pv} and WG^{pv} are as defined in equations (17) to (25). V depends both directly and indirectly, via L^* and h_t^*, on the exogenous SLR trajectory, S_t. Because S_t is a path, rather than a real number, $V(S_t)$ is not a function but a *functional*: a mapping from a curve

[16] A more sophisticated representation may include increased costs from storm damage and salination here, which are neglected in the present formulation.

(S_t) to a real number (V) (see e.g. Chiang, 1992).

In the policy debate different SLR scenarios are usually characterised by the rise expected at a certain benchmark date (e.g. 1 metre by 2100). It would therefore be desirable to express the costs of SLR as a function of such a benchmark figure, rather than using the less accessible notion of a functional. To achieve this, the range of possible SLR paths is limited to one particular form, viz. it is assumed that the sea level rises linearly over time, and reaches a height of S_τ at the end of the time horizon. Normalising the initial levels at $G_0 = S_0 = 0$, this implies

$$S_t = S_\tau \cdot \frac{t}{\tau} \tag{27}$$

Thanks to this assumption the costs of SLR can now be expressed as a function of S_τ, compatible with the custom in the policy debate.

It is now also possible to undertake comparative static analysis. It is relatively easily shown that both h_t and V depend positively on S_τ, i.e. $\partial h_t/\partial S_\tau$, $\partial V/\partial S_\tau > 0$. More interesting is the sign of $\partial L^*/\partial S_\tau$. By substituting for h_t and G_t in (18) and (24) we can eliminate these two variables and L^* becomes a function of S_τ alone. Differentiating the resulting expression and rearranging yields (for an interior solution)

$$\frac{\partial L^*}{\partial S_\tau} = (1-L^*)\left[\frac{DL^{pv\prime}}{DL^{pv}} - \frac{PC^{pv\prime}+WG^{pv\prime}}{PC^{pv}+WG^{pv}}\right] \tag{28}$$

where $PC^{pv\prime}$, $WG^{pv\prime}$ and $DL^{pv\prime}$ denote the first order derivatives of PC^{pv}, WG^{pv} and DL^{pv}, respectively, with respect to S_τ. It is easily shown that the sign of $PC^{pv\prime}$ and $DL^{pv\prime}$ is positive, while $WG^{pv\prime}$ is equal to zero. The sign of $\partial L^*/\partial S_\tau$ is therefore ambiguous. However, equation (28) has an easy interpretation, as follows.

A high SLR will lead to a higher (lower) level of protection than a modest rise if the percentage rise in costs under full protection - the second term in equation (28) - is smaller (greater) than the percentage rise in costs without any protection - the first term in equation (28).

5. SLR COST ESTIMATES FOR OECD COUNTRIES

Several data sources are available to calibrate the model on real data, most notably IPCC (1990), but also Titus *et al.* (1991) and Rijsberman (1991). It should however be emphasised that, as with all estimates on global warming damage, the reliability of many of these figures is rather low, and this will also affect the quality of the simulation results. A considerable range of error has therefore to be accounted for. Simulations will be carried out for the countries of the OECD, for a time horizon of 110 years, i.e. until the year 2100.

When estimating the costs of SLR we have to be aware of the fact that different types of coasts will warrant different measures of protection. IPCC (1990) has distinguished between 4 coastal types, cities, harbours, beaches, and open coasts. We will follow this and calculate the costs for each of these categories in each country. The total costs of SLR in a country will then be the sum of these four categories. Following IPCC (1990) we assume that beaches will be conserved through beach nourishment, while all other types will be protected by sea dikes.

5.1 Estimation of Parameters

Parameters were estimated using the work of IPCC (1990), Rijsberman (1991) and Titus *et al.* (1991). Appendix 1 contains a full list of all relevant values. Some values could be taken directly from these sources, some had to be adjusted for the present purpose.

The length of threatened coastlines was taken from IPCC (1990). In the case of open coasts the data were supplemented with figures from Rijsberman (1991) on sparsely populated coasts. Estimates for coastal wetland areas were taken from the same source[17]. It was assumed that such wetlands only occur along open coasts. To convert Rijsberman's area estimates into lengths of coastline, equation (13) was calibrated to match the US data from Titus *et al.*. We found that 1 km^2 of wetlands roughly corresponds to 1 km of wetland coastline. That is, wetlands are about 1 km wide. The same procedure simultaneously also determined the wetland migration rate α. The dryland loss and protection cost parameters Ψ and γ were calibrated in a similar way. For all three parameters - α, Ψ and γ - the US value was assumed to hold in all countries.

Differences in protection costs between countries manifest themselves in parameter _, which was determined from the IPCC (1990) data. It contains construction as well as maintenance costs. Countries also differ with respect to land prices (parameters x_0 and x_0^W). OECD wide average values were set at 2 m$/km^2 for open coasts and beaches, and 5 m$/km^2 for wetlands (Fankhauser, 1993; 1992). The land value for cities and harbours was set at 200 m$/km^2, the highest value reported in Rijsberman (1991). This was sufficient to guarantee an almost complete level of protection of these two coastal types. For lack of country specific data, regional land values were then compiled by multiplying the OECD average with a series of indicators[18]. These included relative wealth (GNP/capita relative to OECD average) for cities and beaches; GNP/land mass (net of wilderness areas) and percentage of urban population in coastal cities for open coasts - the former an indicator of the scarcity of land, the later an indication of the relative importance of coastal zones; and international tourist revenues per km of coast for beaches to measure the relative importance of tourist beaches[19].

Global predictions of income and population growth were taken from IPCC (1992a), whose estimates are themselves based on World Bank and UN data. Country estimates were then achieved by weighting the OECD average with indicators of past economic performance, and short term predictions on future population growth.

The discount rate was determined in the manner suggested by Cline (1992a). Non consumption based costs - all protection costs, 20% of dryland loss and 10% of wetland loss - are transformed into consumption units by multiplication with the shadow value of capital, and then discounted at the rate

$$r = \rho + \omega \cdot y \tag{29}$$

where ρ is the utility discount rate or social rate of time preference; ω is the income elasticity of marginal utility, and y the rate of growth of per capita income. That is, the discount rate consists of two factors, time preference (or impatience) and the effect of decreasing utility of income as nations become richer. See Cline (1992a) or Lind (1982) for details. Based on empirical evidence cited in Cline (1992a) we assumed $\omega = 1.5$. Estimates of income growth were taken from IPCC (1992a), as mentioned above.

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[17] Unfortunately, no figures were available for Australia, Canada and New Zealand.

[18] All indicators were normalised to the OECD average, i.e. the OECD value of each indicator is one.

[19] The indicator is not ideal because (a) it neglects domestic tourism and (b) it also encompasses tourist activities other than beach recreation. It will thus underestimate beach values in countries where domestic tourism is important, such as the US, and overestimate the value in countries where non-beach tourism dominates.

The controversial parameter in this equation is ρ (see e.g the discussion in Cline, 1992a; Pearce and Markandya, 1991). Here we work with two scenarios. The main results are based on a value of $\rho=0$. As a sensitivity test we also calculated figures for $\rho=0.03$. The first case follows the argumentation of Cline (1992a), Ramsey (1928), and Solow (1974, 1992), among others, who reject a positive rate as individually irrational and ethically unjustifiable since it gives a lower weight to future generations. The second scenario is along the lines of Nordhaus (1992), who observed that only a positive rate is compatible with historically observed savings and interest rate data. To be consistent with Nordhaus we assumed $\omega=1$ in the high discounting case. For a further discussion see e.g. Broome (1992), Cline (1993) and Birdsall and Steer (1993).

5.2 The Optimal Level of Protection

The results with respect to the optimal degree of coastal protection are summarised in Figures 3 and 4. The detailed set of results is given in Appendix 2[20]. Not surprisingly the highest degree of protection is achieved in cities and harbours, where the protection rate is nearly 100% in all countries and for all SLR scenarios. The value of the land at threat is sufficiently high to justify full protection. The picture is somewhat more dispersed in the case of open coasts and beaches, where the optimal level of OECD-wide protection varies between about 75% - 80% and 50% - 60%, respectively (see Figure 3).

How will the optimal degree of protection change for different assumptions about SLR? Section 4.3 showed that the sign of the first order derivative of L^* with respect to the expected SLR, $\partial L^*/\partial S_T$, is ambiguous and depends on the relative costs of full retreat vis à vis the costs of full protection (see equation (28)). The numerical simulations now show that in the case of cities and harbours the protection cost element tends to dominate. That is, the optimal level of protection decreases as predictions about SLR increase, although, to be sure, the figures are still not significantly different from 100% even in the worst case. Interestingly this trend is reversed in the case of beaches. Here the potential land loss damage dominates and the optimal level of protection increases as expectations of SLR become more pessimistic. In a majority of countries the same seems to be true for open coasts (see Appendix 2). The aggregate picture over the whole OECD (Figure 3), on the other hand, shows a decreasing level of protection at least for higher degrees of SLR. This may however be an artefact of the poor data quality. The aggregate seems to be heavily influenced by the three countries Australia, Canada and New Zealand, for which wetland figures are missing, and for which the cost of

[20] We only report estimates for SLR scenarios of more than 20 cm. For low enough scenarios the function will exhibit a discontinuity at the point where equation (13) ceases to hold (see footnote 11).

protection element is therefore strongly dominant.

The regional picture can deviate considerably from the OECD average. Figure 4 shows countrywise estimates of the optimal protection of beaches and open coasts against a 1 metre SLR. The values for cities and harbours are not reported in the Figure. They exhibit less variation and are close to 100% for all countries (see Appendix 2 for details). Regional differences are mainly driven by differences in the value of dry- and wetland. Poorer nations such as Turkey and large countries such as Australia and Canada tend to have lower protection levels, caused by lower land values[21]. The same is true for countries with a low population density such as Iceland and Norway. In the case of Canada a low land value is further coupled with comparatively high protection costs which leads to optimal protection levels clearly below 50%. Densely populated countries like the Netherlands, on the other hand, have protection values close to 100% even for a low SLR (see Appendix 2). Low land values are offset by comparatively low costs of protection in relatively poor Portugal and Ireland. In the case of beaches the protection is increased in countries like Greece and Spain because of the importance of summer tourism in these countries. The low figure for the US on the other hand is mainly due to the inaccuracy of the utilised index of beach tourism (see footnote 19).

It should be recalled that these figures are only indicative of the optimal protection levels. As emphasised in the beginning, the design of the optimal SLR mitigation strategy is genuinely a regional problem which will and should be solved at a local level.

5.3 The Costs of SLR

The results of the numerical simulations of equation (26) are depicted in Figure 5, for the OECD as a whole, and Figure 6, for individual countries. Detailed results are given in Appendix 3. The Figures show the costs of SLR as a function of the rise expected by the year 2100. Costs are expressed as the present value of a stream of expenditures over the next 110 years. They differ widely between countries, ranging from less than 10 bn$ to over 400 $bn for a 1 metre rise, although the values are below 100 bn$ for all but two countries (see Figure 7). Consistent with earlier results (Fankhauser, 1993; 1992) the bulk of damage stems from wetland loss. Dryland losses tend to be comparatively moderate and are restricted to low value areas, due to the generally rather high protection levels.

[21] Recall that for Australia, Canada and New Zealand no wetland figures were available. The reported figures thus overestimate the optimal protection level for these regions (see equation (24)).

Estimates strongly depend on the choice of the discount rate, as is shown in Figure 7. All results presented so far were based on the assumption of zero utility discounting, and an income elasticity of utility of 1.5, consistent with Cline (1992a), see section 5.1. Alternatively, if we use the Nordhaus (1992, 1993) assumption of a 3% utility discount rate, coupled with a marginal utility of income of 1, costs are reduced by as much as a factor 3 on average (see Appendix 3 for details).

Damage raises rather rapidly as SLR predictions increase. Figures 5 and 6 show SLR damage functions which are only slightly convex and almost linear. Although it is usually assumed that damage is a convex function of climate change this should not surprise us. Recall that the functions in Figures 5 and 6 are minimum functions. As such they necessarily have to be less convex than the fixed-policy-response functions which they envelop, and on which convexity predictions are usually based. Further, the main source of non-linearity is typically the construction costs of sea walls, which rise more than linearly with the required height, and thus with SLR. With respect to land loss, the relationship is more likely to be linear (see Figure 1), and these costs, particularly wetland damage, dominate the total.

Because the figures presented here are in present value terms, they are not directly comparable to those of most other studies, which typically only assess the one off costs of protection and/or the value of assets at threat. To the extent that a comparison is possible, results appear to be within the same order of magnitude, however.

6. SUMMARY AND CONCLUSIONS

The aim of the paper has been twofold. First we wanted to exemplify the relative role of mitigation expenditures within the costs of greenhouse damage in general, and for SLR in particular. We derived a rule of thumb to estimate the socially optimal degree of coastal protection. It was shown that the optimal level of protection is determined by the ratio of costs under full protection against those under full retreat (see equation (24)). The larger the costs of protection, or the lower the damage under full retreat, the lower will be the degree of protection.

In our numerical simulations we found that the optimal degree of protection will vary between about 50% to 80% for open coasts and beaches, depending on the underlying SLR scenario. Cities and harbours are almost invariably protected to the full. A higher SLR will generally lead to a higher degree of protection for beaches, and probably open coasts, but to a lower protection of cities and harbours. Large and sparsely populated, as well as poorer nations tend to require a lower degree of protection. The overall picture, however, appears to be that for the wealthy nations of the OECD it will probably pay off to protect most of their coasts.

The second aim of the paper was to estimate the costs of SLR. The aim was to introduce a model which can provide a rough global assessment of SLR damage, to complement the growing number of more accurate, but geographically limited local case studies. We found that, provided the cost efficient solution is implemented, the costs of SLR will probably not be catastrophically high, at least for OECD countries. Damage costs rise steeply, and almost linearly with the degree of SLR predicted for the end of the planning horizon. By far the most important damage category is the loss of wetlands. It should be clear, however, that SLR costs to the countries of the OECD are only a fraction of total worldwide greenhouse damage. No conclusions can therefore be drawn on the optimal level of greenhouse gas abatement.

A high level of aggregation allowed, and indeed was necessary for, a global assessment of SLR damage. However, it may also be the main weakness of the model. Reducing the set of available policy options and neglecting differences in geographical and socio-economic structures may have biased the result. It is also well known that the value of land is only an imperfect indicator of the true welfare loss to consumers, and for many people their home land may be worth more than just its market value. Further, the resettlement of people from abandoned areas may not take place without friction and may be subject to considerable adjustment costs (see Pearce, 1993). The costs of resettlement of a climate refugee (excluding the disutility from hardship) have been assessed at about $ 4,500 per person (Cline, 1992a; Ayres and Walter, 1991; see also Fankhauser, 1993; 1992). These were neglected here, and the figures presented here are therefore likely to underestimate the true costs. The model would then also underestimate the optimal level of protection.

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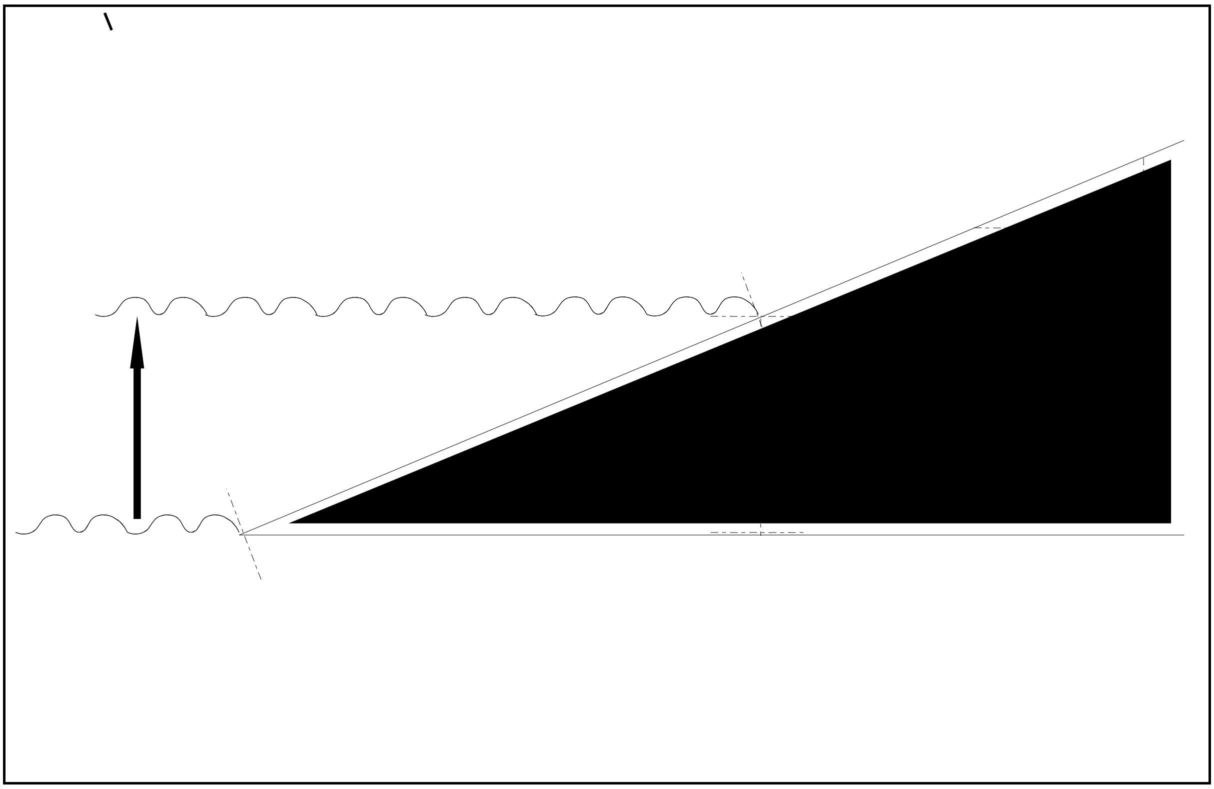
FIGURE 1: SLR AND THE LOSS OF UNPROTECTED LAND



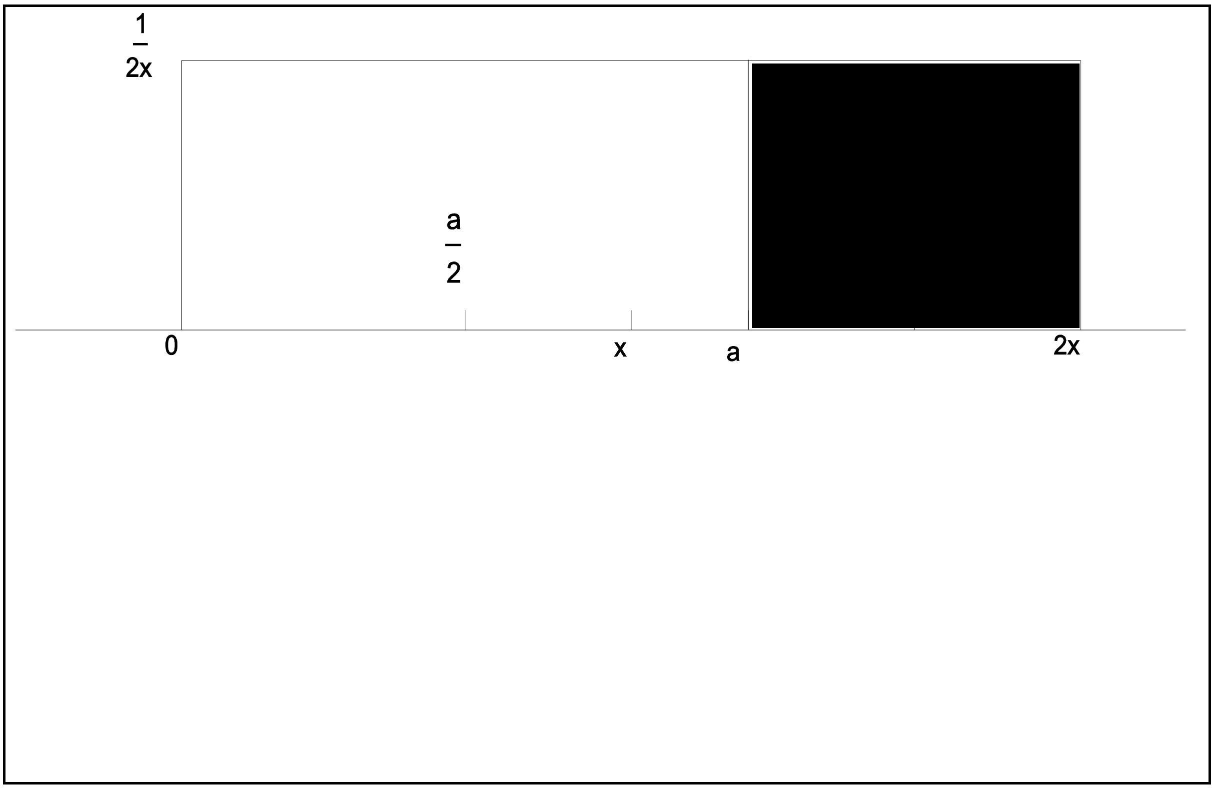
Suppose the sea level is rising by the amount S. We are interested in the resulting loss of unprotected land l. Suppose further that the coastline has a slope of 1/z. The loss in land l will then be

$$l = \sqrt{S^2 + z^2 S^2} = \sqrt{S^2 (1 + z^2)}$$

The loss of unprotected land is therefore proportional to the rise in sea level, l = ψS, where the factor of proportion ψ is defined as

$$\psi = \sqrt{1 + z^2}$$

FIGURE 2: LAND VALUE DISTRIBUTION AND THE VALUE OF PROTECTED AND UNPROTECTED LAND



Suppose dryland has an average value of x. The maximum value observed is 2x, the minimum is 0, and all values are equally likely. Suppose all land with a value greater than a is protected. The expected value of protected land then is (2x+a)/2, that of unprotected land a/2. Note that the more land protected, i.e. the lower a, the lower will be the average value of the remaining unprotected land. From section 2 we know that the value of the last protected zone, a, is a function of L, a = a(L), with the properties a(0) = 2x (the first zone protected has the maximum value 2x) and a(1) = 0 (the last area protected has value zero). A functional form with the desired properties is a = 2x(1-L), which implies average land values of x(2-L) for protected areas and x(1-L) for coasts without defence.

FIGURE 3: OPTIMAL COASTAL PROTECTION IN THE OECD

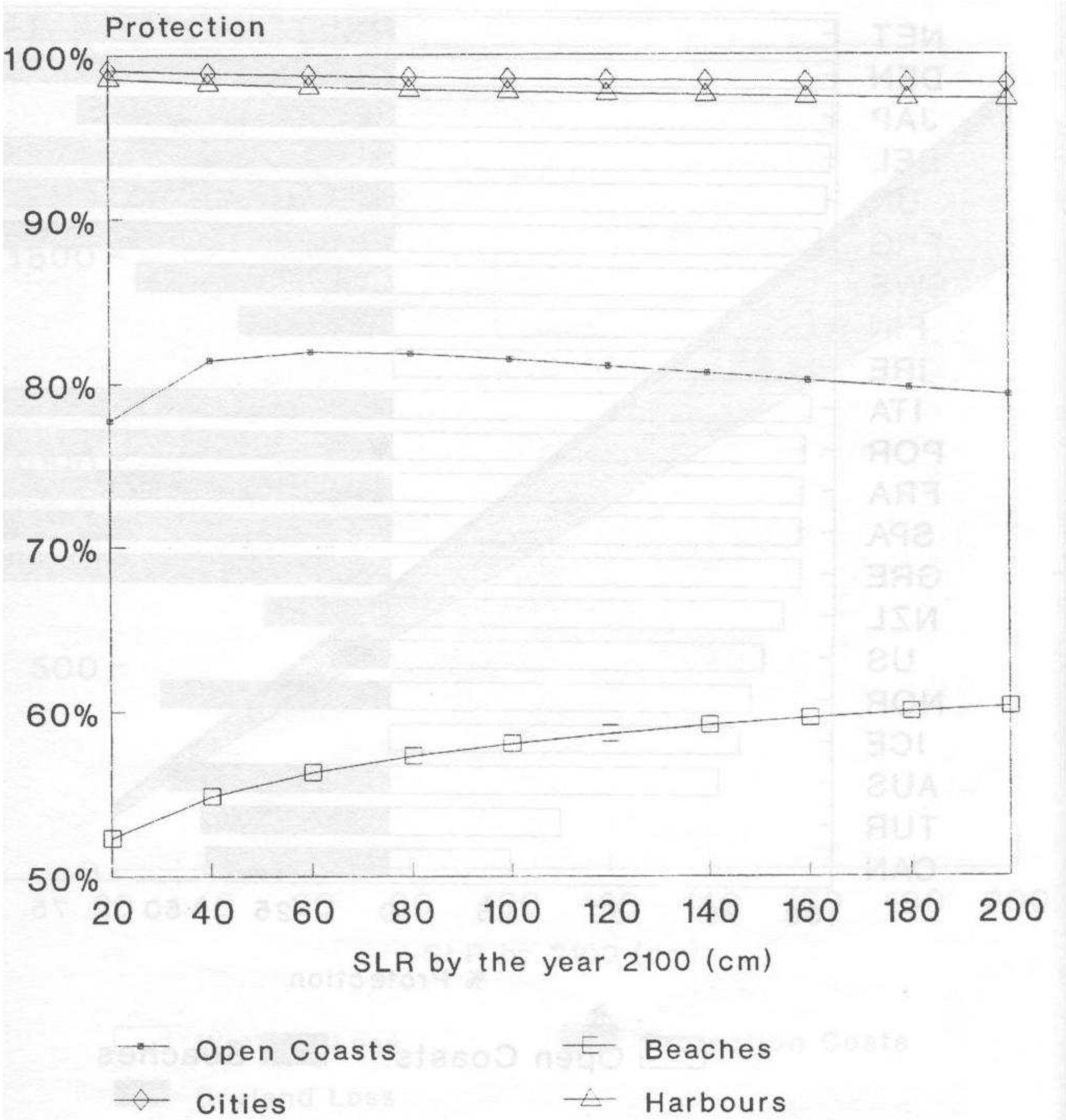
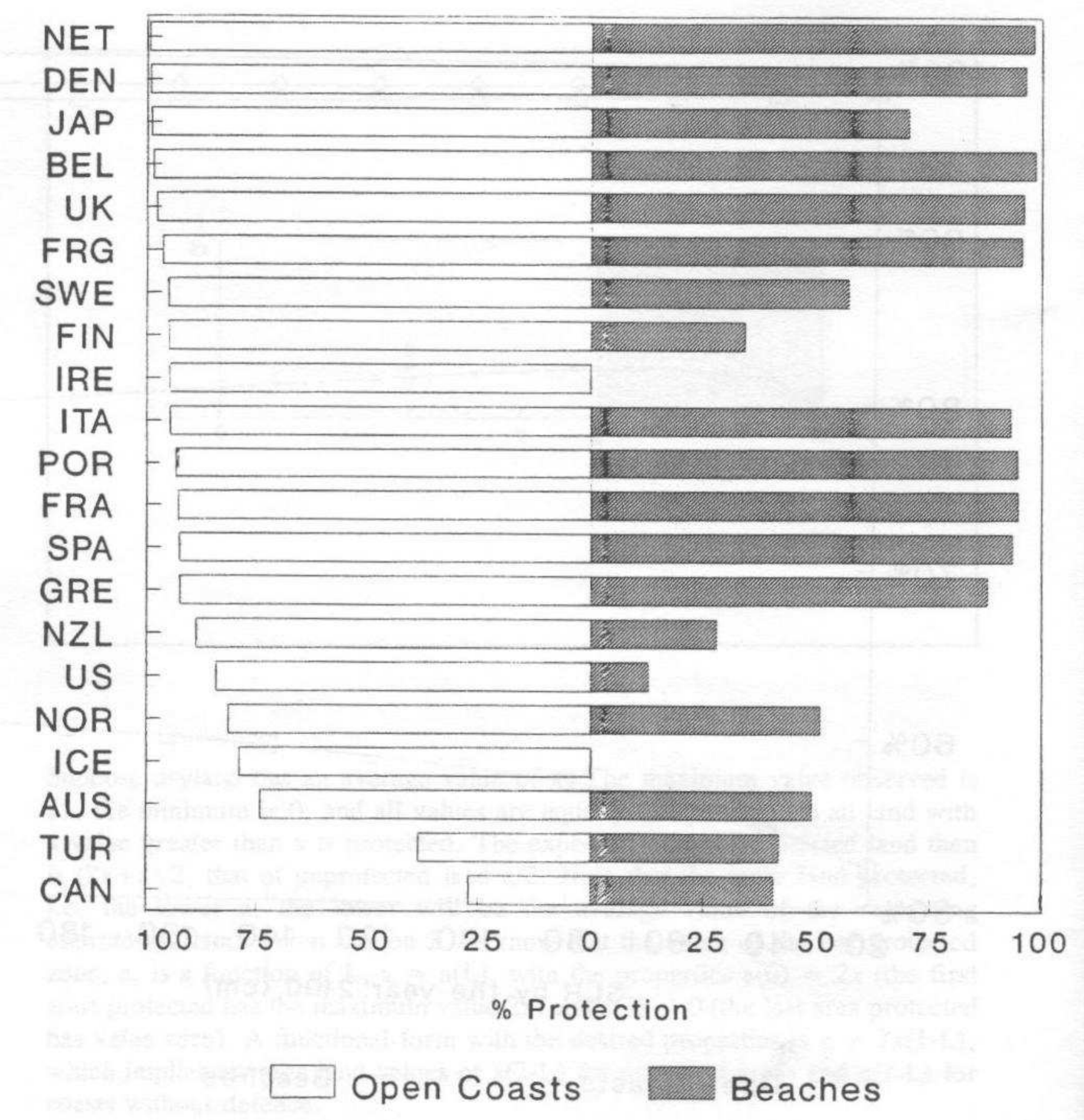


FIGURE 4: OPTIMAL PROTECTION IN OECD COUNTRIES AGAINST A 1 METRE SLR



For details see Appendix 2

FIGURE 5: THE COSTS OF SEA LEVEL RISE IN THE OECD

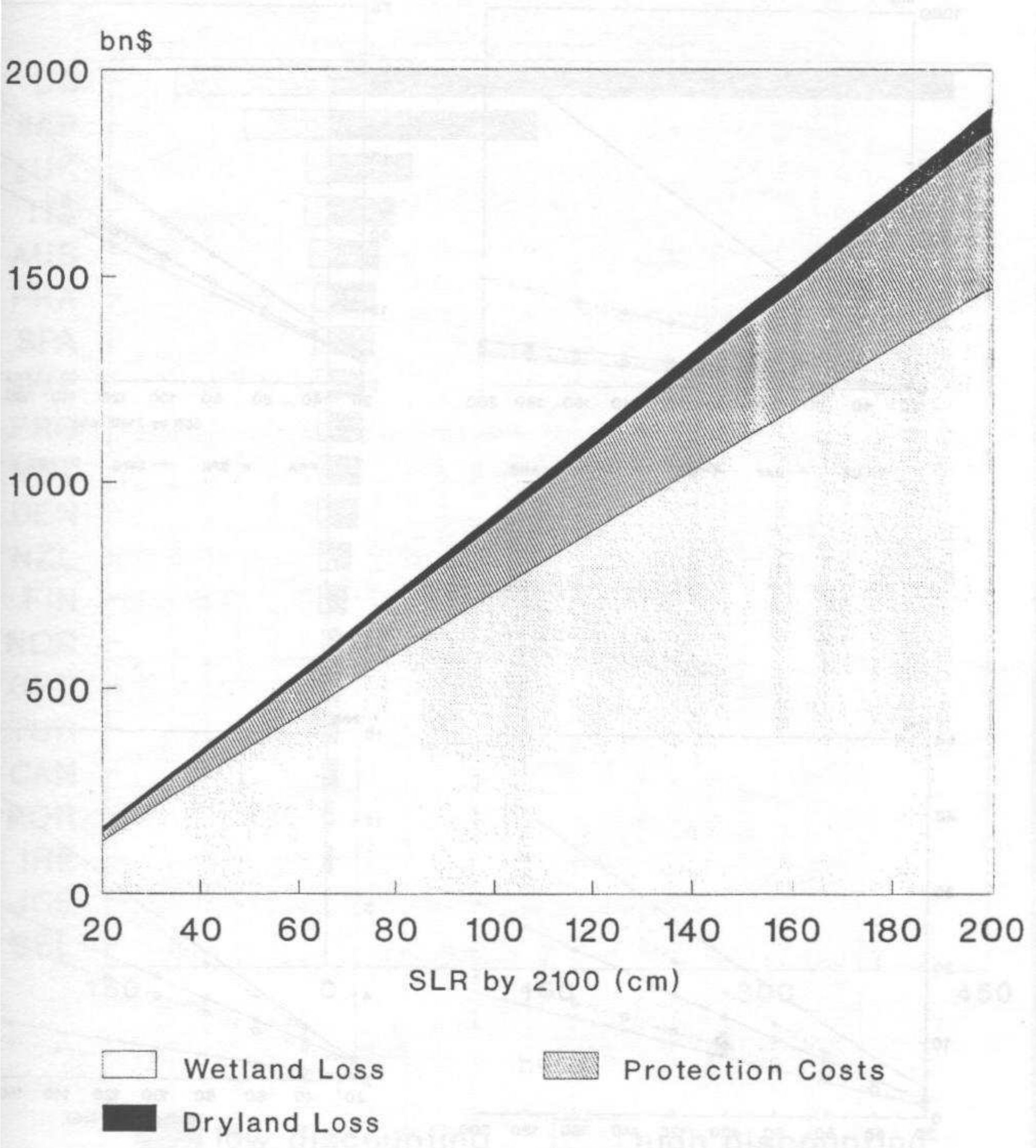


FIGURE 6: THE COSTS OF SEA LEVEL RISE IN OECD COUNTRIES

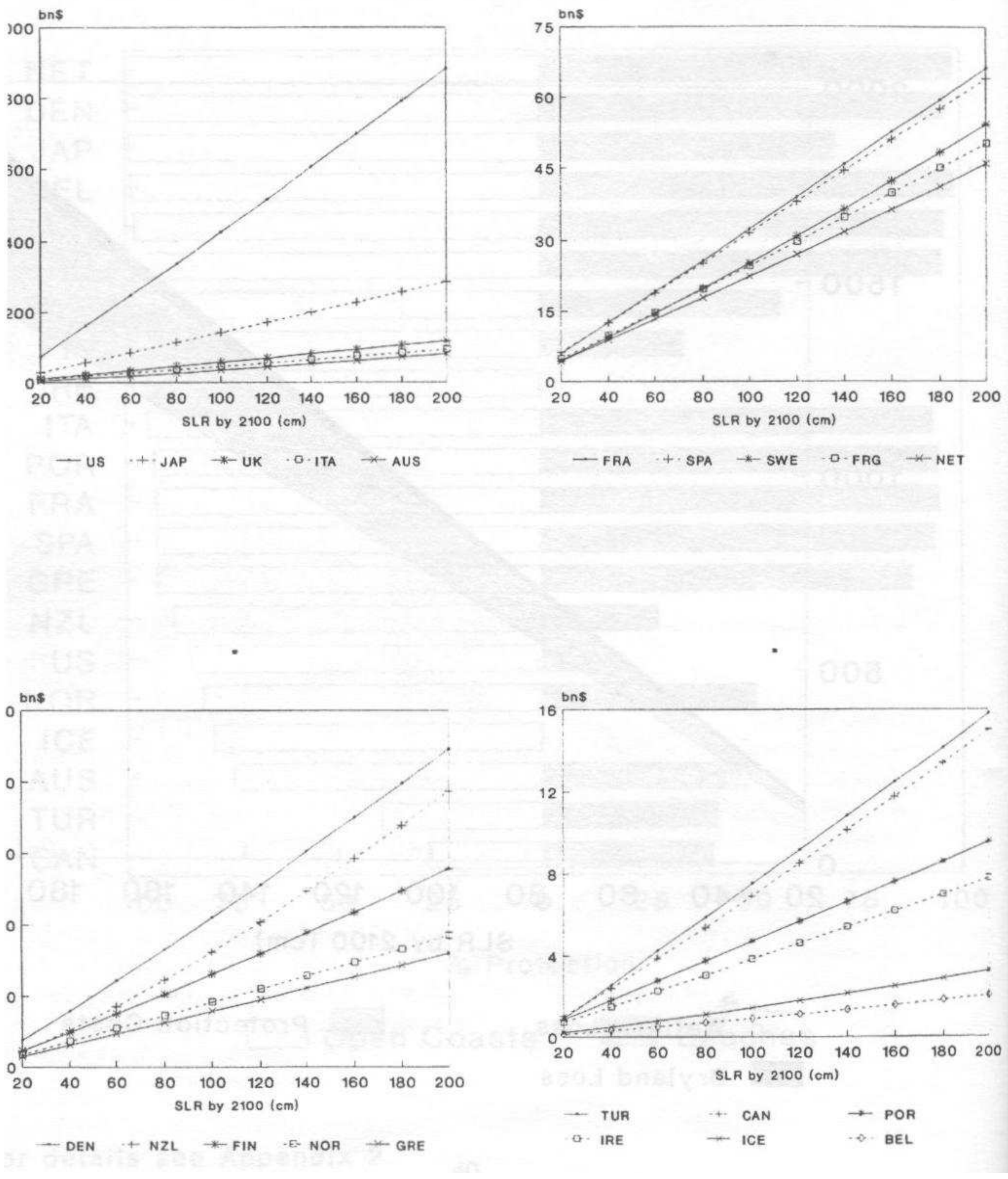
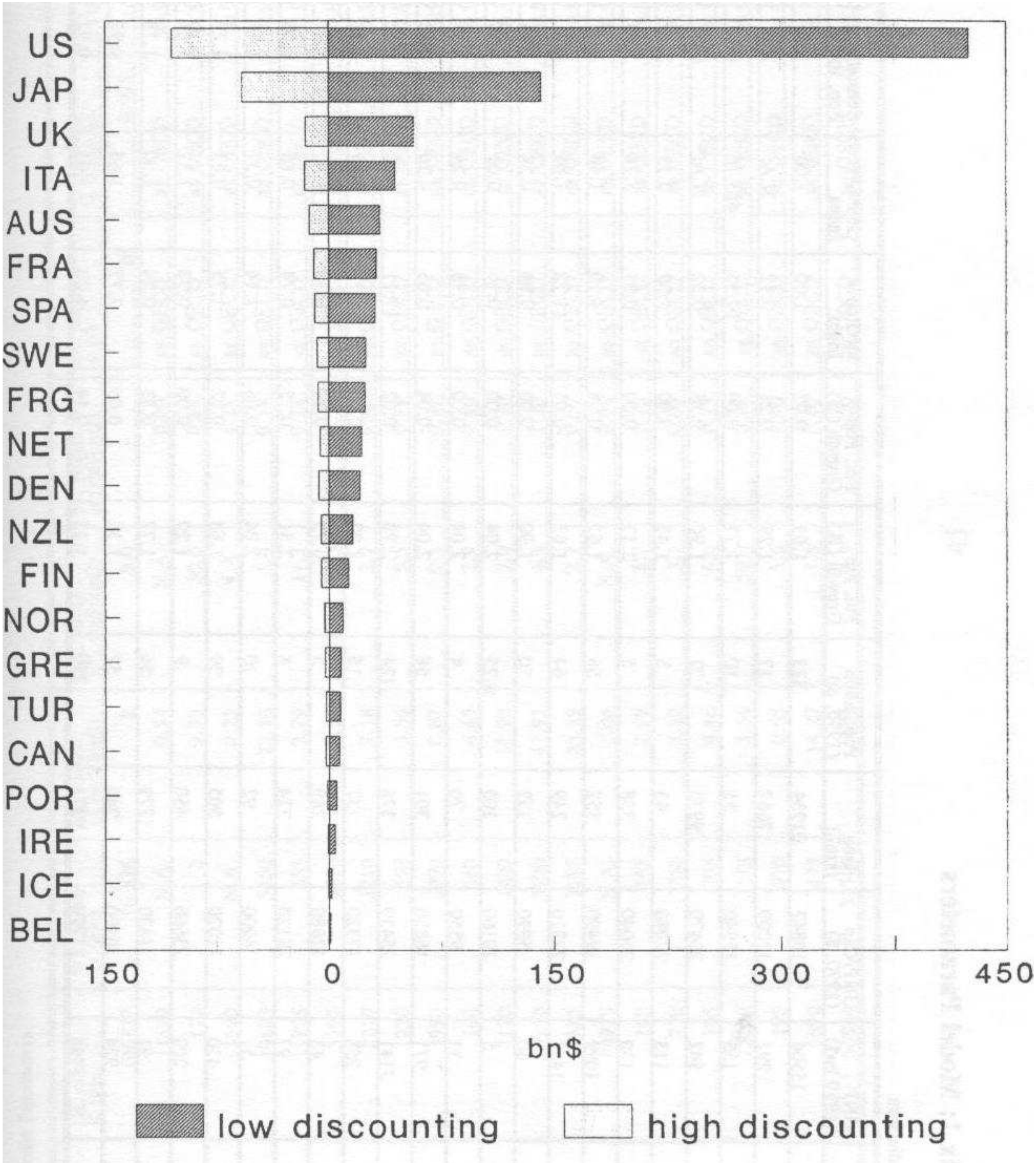


FIGURE 7: THE COSTS OF A 1 METRE SLR - HIGH AND LOW DISCOUNTING



Appendix 1: Model Parameters

(a) Basic Indicators

	GNP (1990 bn$)	GNP/Cap (1990, $)	Area (km2)	Population (1990, m)	Fut. Inc Growth (%)	Fut. Pop Growth (%)	GNP/area Index	GNP/WL Index	Coastal Pop. Index	Tourism Index
OECD	15504	18847	31934	823	1.63	0.07	1.00	1.00	1.00	1.00
AUS	291	17000	7687	17	1.29	0.21	0.12	N.A.	2.31	1.13
BEL	155	15540	31	10	1.77	0.00	10.33	483.76	0.47	2.73
CAN	542	20470	9976	27	1.90	0.16	0.32	N.A.	0.35	0.96
DEN	113	22080	43	5	1.43	0.00	5.39	0.13	2.21	2.52
FIN	130	26040	338	5	2.17	0.00	0.87	1.78	1.60	0.86
FRA	1099	19490	552	56	1.63	0.08	4.10	1.48	0.45	1.90
FRG	1417	22320	249	64	1.63	-0.01	11.72	1.86	0.31	0.78
GRE	60	5990	132	10	1.90	0.00	0.94	0.58	1.88	3.88
ICE	5	20160	103	0.25	2.04	0.00	0.14	0.01	2.36	2.39
IRE	33	9550	70	4	2.04	0.00	0.98	0.24	2.36	4.00
ITA	971	16830	301	58	2.04	-0.04	6.65	4.26	0.90	1.48
JAP	3141	25430	378	124	2.78	0.02	17.11	0.70	1.22	0.12
NET	258	17320	37	15	1.22	0.04	14.37	0.44	1.22	1.52
NZL	43	12680	269	3	0.75	0.20	0.33	N.A.	2.21	2.62
NOR	97	23120	324	4	2.31	0.15	0.74	0.86	2.00	1.59
POR	51	4900	92	10	2.04	0.06	1.14	0.37	1.67	5.77
SPA	430	11020	505	39	1.63	0.02	1.75	0.63	1.27	4.10
SWE	203	23660	450	9	1.29	0.00	0.98	7.32	1.81	1.43
TUR	91	1630	779	56	1.77	0.33	0.24	1.00	1.13	3.01
UK	924	16100	245	57	1.36	0.05	7.77	1.66	0.92	1.36
US	5448	21790	9373	250	1.15	0.14	1.20	1.01	0.97	0.72

(b) Open Coast Parameters

	DL coasts K (km)	WL coasts W (km)	DL value x_0 (m$/km2)	WL value x^W_0 (m$/km2)	PC param. _ (m$/km2)	PC param. γ (-)	DL param. ψ (km/cm)	WL migrat α (km/yr)
OECD	196729	96,526	2	5.0	-	1.28	0.005	0.0005
AUS	52310	N.A.	0.54	N.A.	0.90	as OECD	as OECD	as OECD
BEL	170	2	9.73	50.0	0.66	as OECD	as OECD	as OECD
CAN	13660	N.A.	0.23	N.A.	1.20	as OECD	as OECD	as OECD
DEN	10800	5450	23.88	1.4	0.78	as OECD	as OECD	as OECD
FIN	11825	455	2.79	14.3	0.78	as OECD	as OECD	as OECD
FRA	5190	4619	3.67	3.3	0.72	as OECD	as OECD	as OECD
FRG	2210	2210	7.18	2.9	0.66	as OECD	as OECD	as OECD
GRE	1230	650	3.56	5.5	0.78	as OECD	as OECD	as OECD
ICE	1990	1990	0.67	0.1	0.90	as OECD	as OECD	as OECD
IRE	160	160	4.63	2.9	0.66	as OECD	as OECD	as OECD
ITA	3120	1420	11.90	19.0	1.20	as OECD	as OECD	as OECD
JAP	3920	3920	41.92	4.3	1.20	as OECD	as OECD	as OECD
NET	2585	2585	35.19	2.7	0.60	as OECD	as OECD	as OECD
NZL	14975	N.A.	1.46	N.A.	0.90	as OECD	as OECD	as OECD
NOR	165	165	2.98	8.7	0.78	as OECD	as OECD	as OECD
POR	750	750	3.82	3.1	0.66	as OECD	as OECD	as OECD
SPA	705	705	4.46	4.0	0.78	as OECD	as OECD	as OECD
SWE	12700	173	3.56	50.0	0.78	as OECD	as OECD	as OECD
TUR	750	570	0.55	5.6	0.90	as OECD	as OECD	as OECD
UK	6690	3473	14.27	7.6	0.66	as OECD	as OECD	as OECD
US	50824	33700	2.31	4.9	1.20	as OECD	as OECD	as OECD

(c) Beach Parameters

	Beach Length K (km)	WL coasts W (km)	Beach value x_0 (m$/km2)	WL value x^W_0 (m$/km2)	PC param. _ (m$/km2)	PC param. γ (-)	DL param. ψ (km/cm)	WL migrat α (km/yr)
OECD	8380	0	2	5.0	-	0.92	0.005	0.0005
AUS	500	0	2.03	N.A.	6.75	as OECD	as OECD	as OECD
BEL	65	0	56.28	50.0	5.11	as OECD	as OECD	as OECD
CAN	150	0	2.08	N.A.	9.00	as OECD	as OECD	as OECD
DEN	300	0	27.15	1.4	5.85	as OECD	as OECD	as OECD
FIN	100	0	1.50	14.3	6.75	as OECD	as OECD	as OECD
FRA	800	0	15.57	3.3	5.40	as OECD	as OECD	as OECD
FRG	300	0	18.22	2.9	4.95	as OECD	as OECD	as OECD
GRE	600	0	7.33	5.5	5.85	as OECD	as OECD	as OECD
ICE	0	0	0.68	0.1	N.A.	as OECD	as OECD	as OECD
IRE	0	0	7.87	2.9	N.A.	as OECD	as OECD	as OECD
ITA	800	0	19.63	19.1	9.00	as OECD	as OECD	as OECD
JAP	100	0	4.03	4.3	9.00	as OECD	as OECD	as OECD
NET	225	0	43.76	2.7	4.50	as OECD	as OECD	as OECD
NZL	100	0	1.73	N.A.	6.75	as OECD	as OECD	as OECD
NOR	20	0	2.37	8.7	9.00	as OECD	as OECD	as OECD
POR	150	0	13.17	3.1	4.95	as OECD	as OECD	as OECD
SPA	500	0	14.37	4.0	5.85	as OECD	as OECD	as OECD
SWE	200	0	2.80	50.0	6.75	as OECD	as OECD	as OECD
TUR	100	0	1.45	5.7	6.75	as OECD	as OECD	as OECD
UK	400	0	21.14	7.6	4.95	as OECD	as OECD	as OECD
US	2970	0	1.73	4.9	9.00	as OECD	as OECD	as OECD

(d) Parameters, Cities and Harbours

	City Coasts K (km)	City Land val. x_0 (m$/km2)	City prot. _ (m$/km2)	Harb. Coasts K (km)	Harbour val. x_0 (m$/km2)	Harb. prot. _ (m$/km2)	PC param. γ (-)	DL param. ψ (km/cm)
OECD	3850	200	-	891.9	200.0	-	1.28	0.005
AUS	254	416.42	15.0	75.6	416.4	22.50	as OECD	as OECD
BEL	31	77.68	11.0	25.3	77.7	16.52	as OECD	as OECD
CAN	94	76.75	20.0	32.0	76.8	30.00	as OECD	as OECD
DEN	78	518.78	13.0	10.2	518.8	19.51	as OECD	as OECD
FIN	36	442.59	13.0	12.0	442.6	19.51	as OECD	as OECD
FRA	146	92.56	12.0	44.7	92.6	18.10	as OECD	as OECD
FRG	94	72.53	11.0	38.1	72.5	16.51	as OECD	as OECD
GRE	60	119.78	13.0	16.2	119.8	19.51	as OECD	as OECD
ICE	10	503.90	45.0	0.7	503.9	21.43	as OECD	as OECD
IRE	52	238.70	11.0	4.1	238.7	16.34	as OECD	as OECD
ITA	264	159.85	20.0	42.9	159.8	29.98	as OECD	as OECD
JAP	543	330.52	20.0	199.1	330.5	30.00	as OECD	as OECD
NET	51	225.11	10.0	75.9	225.1	14.99	as OECD	as OECD
NZL	151	297.92	15.0	4.6	297.9	22.61	as OECD	as OECD
NOR	48	491.20	13.0	14.7	491.2	19.46	as OECD	as OECD
POR	37	86.96	11.0	5.3	87.0	16.60	as OECD	as OECD
SPA	134	148.74	13.0	39.7	148.7	19.50	as OECD	as OECD
SWE	151	455.36	13.0	21.9	455.4	19.45	as OECD	as OECD
TUR	82	19.56	15.0	25.8	19.6	22.56	as OECD	as OECD
UK	392	156.94	11.0	64.4	156.9	16.49	as OECD	as OECD
US	1142	223.30	20.0	138.7	223.3	30.00	as OECD	as OECD

(e) Discounting Parameters (low / high scenario)

	Future Income Growth y (%)	Rate of Risk Aversion ω	Return on Cap. r (%)	Rate of Time Preference ρ (%)	Shadow Price of Capital	Discount Rate, r (low case)	Discount Rate, r (high case)
OECD	1.63	1.5 / 1	10	0 / 3	1.63 / 1.32	2.45	4.63
AUS	1.29	1.5 / 1	10	0 / 3	1.70 / 1.37	1.94	4.29
BEL	1.77	1.5 / 1	10	0 / 3	1.61 / 1.31	2.65	4.77
CAN	1.90	1.5 / 1	10	0 / 3	1.59 / 1.29	2.85	4.90
DEN	1.43	1.5 / 1	10	0 / 3	1.67 / 1.35	2.14	4.43
FIN	2.17	1.5 / 1	10	0 / 3	1.54 / 1.26	3.26	5.17
FRA	1.63	1.5 / 1	10	0 / 3	1.63 / 1.32	2.45	4.63
FRG	1.63	1.5 / 1	10	0 / 3	1.63 / 1.32	2.45	4.63
GRE	1.90	1.5 / 1	10	0 / 3	1.59 / 1.29	2.85	4.90
ICE	2.04	1.5 / 1	10	0 / 3	1.56 / 1.27	3.06	5.04
IRE	2.04	1.5 / 1	10	0 / 3	1.56 / 1.27	3.06	5.04
ITA	2.04	1.5 / 1	10	0 / 3	1.56 / 1.27	3.06	5.04
JAP	2.78	1.5 / 1	10	0 / 3	1.44 / 1.18	4.18	5.78
NET	1.22	1.5 / 1	10	0 / 3	1.71 / 1.38	1.83	4.22
NZL	0.75	1.5 / 1	10	0 / 3	1.81 / 1.45	1.12	3.75
NOR	2.31	1.5 / 1	10	0 / 3	1.52 / 1.24	3.46	5.31
POR	2.04	1.5 / 1	10	0 / 3	1.56 / 1.27	3.06	5.04
SPA	1.63	1.5 / 1	10	0 / 3	1.63 / 1.32	2.45	4.63
SWE	1.29	1.5 / 1	10	0 / 3	1.70 / 1.37	1.94	4.29
TUR	1.77	1.5 / 1	10	0 / 3	1.61 / 1.31	2.65	4.77
UK	1.36	1.5 / 1	10	0 / 3	1.68 / 1.36	2.04	4.36
US	1.15	1.5 / 1	10	0 / 3	1.72 / 1.39	1.73	4.15

Appendix 2: Optimal Degree of Coastal Protection

(a) Open Coasts (% protected)

	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm	180 cm	200 cm
OECD	78	81	82	82	81	81	81	80	80	79
AUS	84	80	78	76	74	73	72	71	70	69
BEL	98	98	99	99	99	99	99	99	99	99
CAN	53	43	37	31	27	23	20	17	14	11
DEN	99	99	99	99	99	99	99	99	99	99
FIN	92	94	95	95	95	95	95	95	95	95
FRA	77	87	90	92	93	93	94	94	94	94
FRG	89	94	95	96	96	97	97	97	97	97
GRE	77	87	90	92	92	93	93	94	94	94
ICE	82	82	81	80	79	78	77	76	76	75
IRE	83	90	93	94	95	95	95	96	96	96
ITA	80	89	92	94	95	95	96	96	96	96
JAP	97	98	99	99	99	99	99	99	99	99
NETH	98	99	99	99	99	99	99	99	99	99
NZL	93	91	90	89	89	88	87	87	87	86
NOR	22	59	72	78	81	84	85	87	88	88
POR	77	87	91	92	93	94	94	95	95	95
SPA	75	86	90	92	93	93	94	94	94	94
SWE	93	95	95	95	95	95	95	95	95	95
TUR	0	0	14	30	38	44	48	51	53	54
UK	92	96	97	97	98	98	98	98	98	98
US	59	75	80	83	84	85	85	86	86	86

(b) Beaches (% protected)

	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm	180 cm	200 cm
OECD	52	55	56	57	58	59	59	60	60	60
AUS	42	45	47	48	49	50	50	51	51	52
BEL	98	98	99	99	99	99	99	99	99	99
CAN	32	36	38	39	41	41	42	43	43	44
DEN	96	96	96	96	96	96	96	96	96	97
FIN	25	29	31	33	34	35	36	37	37	38
FRA	94	94	94	95	95	95	95	95	95	95
FRG	95	95	95	95	96	96	96	96	96	96
GRE	86	87	87	88	88	88	88	88	88	88
ICE	-	-	-	-	-	-	-	-	-	-
IRE	-	-	-	-	-	-	-	-	-	-
ITA	92	92	93	93	93	93	93	93	93	93
JAP	66	68	69	70	70	71	71	71	72	72
NETH	98	98	98	98	98	98	98	98	98	98
NZL	18	22	25	27	28	29	30	31	31	32
NOR	44	47	49	50	51	52	52	53	53	53
POR	94	94	94	95	95	95	95	95	95	95
SPA	93	93	93	93	93	94	94	94	94	94
SWE	51	54	55	56	57	58	58	59	59	60
TUR	34	37	39	41	42	42	43	44	44	45
UK	96	96	96	96	96	96	96	96	96	96
US	1	6	9	11	13	14	15	16	17	17

(c) Cities (% protected)

	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm	180 cm	200 cm
OECD	99	99	99	99	99	98	98	98	98	98
AUS	100	100	100	99	99	99	99	99	99	99
BEL	99	98	98	98	98	98	98	97	97	97
CAN	98	97	97	97	96	96	96	96	96	96
DEN	100	100	100	100	100	100	100	100	99	99
FIN	100	100	100	100	100	100	100	100	99	99
FRA	99	98	98	98	98	98	98	98	98	98
FRG	98	98	98	98	98	97	97	97	97	97
GRE	99	99	99	98	98	98	98	98	98	98
ICE	99	99	99	99	99	99	99	98	98	98
IRE	100	99	99	99	99	99	99	99	99	99
ITA	99	99	98	98	98	98	98	98	98	98
JAP	99	99	99	99	99	99	99	99	99	99
NETH	100	99	99	99	99	99	99	99	99	99
NZL	99	99	99	99	99	99	99	99	99	99
NOR	100	100	100	100	100	100	100	100	100	100
POR	99	99	98	98	98	98	98	98	98	98
SPA	99	99	99	99	99	99	98	98	98	98
SWE	100	100	100	100	99	99	99	99	99	99
TUR	94	93	92	91	90	90	89	89	89	88
UK	99	99	99	99	99	99	99	99	99	99
US	99	99	99	99	99	98	98	98	98	98

(d) Harbours (% protected)

	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm	180 cm	200 cm
OECD	99	98	98	98	98	98	97	97	97	97
AUS	99	99	99	99	99	99	99	99	99	99
BEL	98	97	97	97	97	96	96	96	96	96
CAN	97	96	95	95	95	94	94	94	94	93
DEN	100	100	99	99	99	99	99	99	99	99
FIN	100	100	99	99	99	99	99	99	99	99
FRA	98	98	97	97	97	97	97	97	96	96
FRG	98	97	97	97	96	96	96	96	96	95
GRE	98	98	98	98	98	97	97	97	97	97
ICE	100	100	99	99	99	99	99	99	99	99
IRE	99	99	99	99	99	99	99	99	99	99
ITA	98	98	98	97	97	97	97	97	97	97
JAP	99	99	99	99	99	99	99	99	99	99
NETH	99	99	99	99	99	99	99	99	99	99
NZL	99	99	99	99	99	99	98	98	98	98
NOR	100	100	100	100	99	99	99	99	99	99
POR	98	98	98	97	97	97	97	97	97	97
SPA	99	98	98	98	98	98	98	98	98	97
SWE	100	99	99	99	99	99	99	99	99	99
TUR	91	89	87	86	86	85	84	83	83	82
UK	99	99	98	98	98	98	98	98	98	98
US	99	98	98	98	98	98	98	97	97	97

Appendix 3: The Costs of Protection

(a) Total Costs $V(S_\tau)$ (low disounting: $\rho = 0$, $\omega = 1.5$; bn$)

	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm	180 cm	200 cm
OECD	164.9	353.6	544.0	737.1	932.5	1129.9	1329.2	1530.1	1732.5	1936.3
AUS	4.8	11.2	18.4	26.3	34.5	43.2	52.2	61.4	71.0	80.7
BEL	0.1	0.3	0.4	0.6	0.8	1.0	1.1	1.3	1.5	1.7
CAN	1.1	2.4	3.8	5.4	6.9	8.5	10.1	11.7	13.4	15.0
DEN	3.8	7.9	12.1	16.5	21.0	25.6	30.2	35.0	39.7	44.6
FIN	2.3	4.8	7.5	10.2	13.1	15.9	18.8	21.8	24.8	27.8
FRA	6.0	12.5	19.1	25.7	32.4	39.1	45.8	52.5	59.3	66.1
FRG	4.8	9.7	14.7	19.6	24.7	29.7	34.7	39.8	44.9	50.0
GRE	1.5	3.1	4.7	6.2	7.9	9.5	11.1	12.7	14.4	16.0
ICE	0.2	0.5	0.8	1.1	1.4	1.8	2.1	2.5	2.9	3.3
IRE	0.7	1.5	2.3	3.0	3.8	4.6	5.4	6.2	7.0	7.8
ITA	8.4	17.6	26.8	36.0	45.3	54.6	64.0	73.4	82.8	92.3
JAP	27.8	56.0	84.3	112.9	141.5	170.2	199.0	227.8	256.8	285.8
NETH	4.3	8.8	13.3	17.8	22.4	27.0	31.7	36.3	41.0	45.7
NZL	2.1	5.1	8.5	12.3	16.2	20.4	24.7	29.2	33.9	38.7
NOR	1.7	3.6	5.4	7.3	9.1	11.0	12.8	14.7	16.6	18.5
POR	0.9	1.8	2.8	3.7	4.7	5.7	6.6	7.6	8.6	9.6
SPA	6.2	12.5	18.9	25.2	31.6	38.1	44.5	50.9	57.4	63.9
SWE	4.4	9.3	14.5	19.8	25.2	30.8	36.5	42.3	48.1	54.1
TUR	0.9	2.6	4.2	5.9	7.5	9.1	10.8	12.5	14.1	15.8
UK	10.8	22.3	33.8	45.5	57.3	69.1	81.1	93.1	105.1	117.3
US	72.3	160.2	247.7	336.0	425.2	515.1	605.8	697.2	789.1	881.7

(b) Sensitivity Analysis: Total Costs $V(S_\tau)$ for high discounting ($\rho = 0.03$, $\omega = 1$; bn$)

	20 cm	40 cm	60 cm	80 cm	100 cm	120 cm	140 cm	160 cm	180 cm	200 cm
OECD	48.2	103.8	160.5	218.4	277.3	337.0	397.4	458.4	520.0	582.2
AUS	1.8	4.3	7.0	9.9	12.9	16.0	19.2	22.5	25.8	29.2
BEL	0.1	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.7	0.8
CAN	0.4	0.9	1.4	1.9	2.4	2.9	3.5	4.0	4.5	5.1
DEN	1.1	2.4	3.8	5.2	6.7	8.2	9.7	11.3	12.9	14.5
FIN	0.9	1.9	2.9	4.0	5.2	6.3	7.5	8.8	10.0	11.3
FRA	1.8	3.7	5.7	7.8	9.8	11.8	13.9	16.0	18.1	20.2
FRG	1.4	2.8	4.2	5.7	7.2	8.6	10.1	11.6	13.1	14.6
GRE	0.5	1.1	1.7	2.3	2.9	3.4	4.0	4.6	5.2	5.9
ICE	0.1	0.2	0.3	0.5	0.6	0.8	0.9	1.1	1.3	1.4
IRE	0.2	0.5	0.7	1.0	1.3	1.5	1.8	2.1	2.3	2.6
ITA	2.9	6.1	9.3	12.5	15.8	19.1	22.4	25.7	29.1	32.5
JAP	11.2	22.6	34.1	45.7	57.4	69.2	81.0	92.9	104.8	116.7
NETH	1.1	2.2	3.4	4.6	5.7	6.9	8.2	9.4	10.6	11.9
NZL	0.7	1.7	2.8	4.0	5.2	6.6	7.9	9.4	10.9	12.4
NOR	0.6	1.2	1.8	2.5	3.1	3.8	4.4	5.1	5.7	6.4
POR	0.3	0.6	0.9	1.3	1.6	1.9	2.3	2.6	3.0	3.3
SPA	1.8	3.6	5.4	7.3	9.1	11.0	12.9	14.8	16.7	18.6
SWE	1.3	2.7	4.3	5.9	7.6	9.4	11.2	13.0	14.9	16.8
TUR	0.3	0.7	1.2	1.7	2.2	2.7	3.2	3.7	4.2	4.8
UK	2.8	5.9	9.0	12.2	15.4	18.6	21.9	25.2	28.6	31.9
US	17.0	38.5	60.2	82.3	104.8	127.6	150.7	174.0	197.6	221.4