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The Value of Perfect Information

- Application to the uncertain time lag of benefits from abatement in the Baltic Sea

Lanya Kawa

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The value of perfect information: application to the uncertain time lag of benefits from abatement in the Baltic Sea

Lanya Kawa

Supervisor: Katarina Elofsson, Swedish University of Agricultural Sciences, Department of Economics

Examiner: Sebastian Hess, Swedish University of Agricultural Sciences, Department of Economics

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Abstract

Eutrophication from nitrogen and phosphorus has damaged the Baltic Sea, leaving large sea bottom areas without biological life, thus changing the marine ecosystem, and triggering the growth of toxic algae. Despite efforts to curb this pollution, the sea remains eutrophic. We argue that eutrophication management is subject to both uncertainty and irreversibility, and hence could explain why impacted countries may not be willing to enforce load reduction targets. This thesis focuses on the time lag of benefits following nitrogen abatement. The time taken for concentration levels to decrease after abatement is uncertain, leading to uncertain benefits. Using the quasi option value model, we calculate the value of learning this information, and thus find that removing this uncertainty is worth over 8.6 billion EUR, to all bordering countries. This could be of significant importance for actors rationally waiting for more information, before implementing expensive and irreversible policy.

Table of Contents

List of Tables

List of Figures

1. Introduction

The Baltic Sea is surrounded by nine littoral countries, all of which benefit from its amenities and ecosystem services. However, these services are at risk due to an excessive pollution of nitrogen and phosphorus. The over enrichment of these nutrients are referred to as eutrophication. This has caused severe environmental concerns; decreased water transparency, growth of toxic algae, which when decays cause a depletion of oxygen levels, altering the marine ecosystems. An example being diminishing fish and seal stock. Human activities have affected the natural processes of the sea, and are considered to be one of the main causes of this over enrichment (Smith et al 1999). The use of phosphorus detergents and chemical fertilisers for example, have greatly increased the amount of nitrates and phosphates that are washed into lakes and ponds.

The Baltic Sea is one of the largest brackish water basins in the world. It can be separated into seven main basins as shown in Figure 1 (Bothnian Bay, Bothnian Sea, Baltic Proper, Gulf of Finland, Gulf of Riga, Danish Straits, and Kattegat). These basins differ considerably in their characteristics, including ice cover, temperature, and water residence time. The sub-basins differ not only in size, volume, and depth, but also in the salinity of the water, which is crucial for animal and plant life (HELCOM 2009). The large catchment area combined with associated human activities, and a small body of water, with limited exchange with the Skagerrak and the North Sea, makes the Baltic Sea vulnerable to nutrient enrichment and eutrophication (HELCOM 2009). The first signs of eutrophication emerged in the mid 1950's (Andersen et al 2015).

Eutrophication is a significant issue for the littoral countries, and has resulted in mounting pressure on their respective governments, to act and enforce policies to reduce this pollution. The Helsinki Commission (HELCOM) was set up in 1974 (the contracting parties are Denmark, Estonia, the European Union, Finland, Germany, Lithuania, Poland, Russia and Sweden) with the aim of protecting the marine environment of the Baltic Sea, from all sources of pollution through intergovernmental cooperation. Original efforts aimed at cutting emission (nitrogen and phosphorus) to the sea by 50%, set in the late 1980's were never met. In 2007 the Baltic Sea Action Plan (BSAP) readdressed previous targets, and outlined new country wise nutrient input reduction targets. These reductions are based on the current input and previous reduction efforts (Tynkkynen et al 2014). However, the sea still remains eutrophic.

In this thesis we argue that countries may be reluctant to commit to load reduction targets, due to the associated uncertainties and irreversibilties of eutrophication management. Firstly, it is unclear what the expected costs and benefits from abatement policies are. The impacted countries may therefore be unwilling to invest in nutrient reduction strategies, if deemed to be unprofitable in the long run. Although a large body of literature has attempted to clarify costs and benefits (Turner et al 1999, Gren et al 1997a, Gren et al 1997b, Gren et al 2008a), these values are often derived using numerous assumptions, and so needs to be taken with caution. Secondly, the different characteristics of the of the Baltic Sea basins, means cost effective reductions can vary between basins (Gren 2008b). Thus leading to further uncertainty on the actual reductions that should be employed. Another uncertainty relates to the nutrient limiting growth in a particular basin. Although both nitrogen and phosphorus cause eutrophication, some basins are nitrogen limited, and hence algae production is only affected by changes in nitrogen concentrations, not phosphorus (see e.g Conley et al 2002, Wasmund and Uhlig 2003, Tamminen and Andersen 2007). These are just some of the uncertainties that face decision makers when selecting appropriate policies. Environmental decisions are often regarded as irreversible, for example, selecting ambitious abatement policies leads to large forgone investment costs. Thus policy makers are unlikely to revoke expensive strategies once they are implemented.

In this thesis we focus on the uncertain time lag of benefits following nitrogen abatement. The time taken for abatement policies to lead to reductions in concentration levels of nitrogen in the sea are uncertain, hence benefits from nitrogen abatement are uncertain. Elofsson (2003) and Gren (2008c) have studied the stochastic relationship between abatement measures and the impact on nutrient loads. They find the covariance of nutrient loads in a region largely affect the abatement policy that should be employed, not accounting for this covariance can lead to under abatement. While Hökby and Söderqvist (2003) states that a 50% reduction of nitrogen loads, corresponds to a 30-50% reduction in concentration levels. However, no previous studies have focused on the uncertain time lag of benefits following abatement. We contribute to this discussion by valuing perfect information regarding the uncertain benefits achieved through nitrogen reductions.

The time taken for nutrients to be removed from the Baltic Sea can fluctuate between basins, due to the different residence times of the water among basins (HELCOM 2009). If concentration levels fall quickly once nutrient reductions are made, then benefits will be received early. However, if concentration levels take a long time to adjust, benefits will be delayed. The literature is this field demonstrates the uncertainties faced. Savchuk and Wulff (1999) used a reduction scenario simulation to estimate the effects of a 50% load reduction to the Baltic Sea. They found that although the time scales for recovery could take decades, reductions of concentration levels were pronounced in Eastern Gulf of Finland after just two weeks. This is a unique case and caused by the short freshwater residence time of the basin, and thus does not apply to all basins. While Stålnacke et al (2003) finds a large reduction of fertiliser and manure use, coupled with increased animal slaughtering in Estonia, Latvia and Lithuania, does not lead to a significant downward trend of nutrients during a 10 year period. Wulff et al (2007) models the response of the Baltic Sea to different management options, and finds it could be decades before any real change is seen. This highlights the inconsistencies in the literature, regarding outcomes of the sea following various abatement strategies. In this thesis we attempt to address this issue by using the quasi option model to determine the value of information on the uncertain time lag of benefits following abatement policy. This is where we attach a monetary value to this uncertainty.

Figure 1. Main basins of the Baltic Sea.
Source: eoearth.org.

1.1 Purpose of Study

Since abatement policy for the Baltic Sea is subject to both uncertainty and irreversibility, it is crucial governments of the surrounding countries are well informed before acting. The quasi option value method defines the time value of waiting until more information is received, before making expensive irreversible policy decisions. Our research will estimate the value of eliminating the uncertainty of the time lag of benefits after abatement, thus justifying if funding this research is beneficial. Therefore, our research question is as follows; *what is the value of perfect scientific information concerning the uncertain time lag of benefits from nitrogen abatement?*

Our research is of value to the affected countries as well as HELCOM. We argue the low implementation of load reduction targets thus far, may be explained by countries rationally waiting to obtain more information about the benefits, before committing to expensive and irreversible polices. By valuing the uncertainty, this should motivate the affected parties to commit to abatement.

We consider two types of abatement polices facing the nine surrounding countries of the Baltic Sea. This occurs over two time periods. One requires a large reduction in nitrogen, and is based on reduction requirements from HELCOM. This policy is assumed irreversible, so once taken in period one, must also be taken in period two. The other is a smaller reduction policy, and corresponds to the actual reductions made. We assume if this policy is taken in period one, we can in fact switch to a high level of abatement in period two. Benefits from each policy are assumed to appear in two uncertain states of the world, one where benefits are received early, and the other where they are delayed. We use the net benefits under all policy options to calculate the quasi option value. The quasi option value here corresponds to the value of information from removing the uncertainty of being in a world with early or late benefits.

Despite the successful use of the quasi option value method in numerous environmental problems, it has not been used to address uncertainties in the Baltic Sea. In fact, to the best of our knowledge, no previous literature has attempted to quantify the value of information concerning uncertainties in Baltic Sea policy. Therefore, our research makes a valid contribution on a scientific basis. Looking at this research on a social perspective, 15 million people live within 10km of the Baltic coast (Sweitzer et al 1996). When algae decays, not only does it cause oxygen depletion, but it also drifts ashore with a pungent smell, and may produce toxic substances (Elofsson 2003). Therefore, this type of research is of particular importance to the people living around the Baltic Sea, who are ultimately the ones most affected by this pollution. Our findings may contribute to these countries implementing better informed abatement policies.

Our research is limited to only considering nitrogen abatement, although both nitrogen and phosphorus cause harm to the Baltic Sea. This may therefore overestimate the benefits we achieve, since we assume all basins benefit from nitrogen reduction equally. Furthermore, the value of information is considered on an aggregate level. Although we find a high quasi option value, this does not necessarily mean all countries benefit to the same extent from having this information. This is a possible ethical issue of our research. Our answers may change if we consider the value of information separately for each country, with some countries benefiting less from this knowledge compared to others.

The remainder of this thesis is structured as follows, section 2 reports on the previous literature in this field. We consider studies that have looked at uncertain outcomes of abatement policy in the Baltic Sea, as well as the application of quasi option value in other fields of research. Section 3 outlines how we apply our work to the quasi option value model. Section 4 simply illustrates the methods we undertake to calculate costs and benefits, and how we will use this information to calculate the quasi option value. Section 5 reports the results of our method. We conclude in section 6 with a discussion on the thesis.

2. Literature Review

Despite its equivalence to the value of information, no previous work has used the quasi option value method to value uncertainties in the Baltic Sea. There is however, a large body of literature that has looked at numerous uncertainties affecting the Baltic Sea, and how they affect policy choices. While the quasi option value model has been successfully incorporated in other fields of research.

The uncertainty of the stochastic relationship between abatement measures and the corresponding impact on nutrient loads is explored in Elofsson (2003). This paper considers a model of point and non-point emission sources, to determine the cost effective solutions of nutrient load reductions to the Baltic Sea. The nutrient loads transported to the sea can vary over seasons and across years. They report some of the factors responsible for this difference include the inconsistency of precipitation and air temperature, while storms can increase the surface- relative to subsurface-runoff. The different uses of land are also another reason for this variability. The lack of information makes policy concerning the correct reduction load to implement subject to uncertainty. This study considers how the variance and covariance of loads from different regions affect cost effective abatement.

They model a large watershed where pollution arises from point and non-point sources, point sources are located at the coast and deemed non-random, and by assumption have a variance of zero. Non-point sources instead are at a distance and stochastic, a fraction of these nutrients are retained (e.g. in soil or lost in air) when traveling to coastal waters. The fraction retained varies between regions, thus the final loads to coastal waters are uncertain. They determine the optimal level of abatement by solving a cost minimisation problem, with respect to different pollutant load reduction measures.

Their results indicate that the cost of reducing nutrient loads by 50% can be 80% higher if the policy maker takes load variation into account. If the covariance of loads between regions are not considered, then costs could be underestimated by 20%. When loads from a region are negatively (positively) correlated, it becomes cost effective to reduce (increase) abatement in that region. This paper successfully highlights the importance of nutrient variations, and the corresponding effects on abatement policy. However, a point of concern is that the researchers only consider a 50% reduction in nutrient loads. Therefore, the conclusions drawn may vary if other load reductions are considered.

Gren (2008c) also considers the stochastic pollution of water. Similarly to Elofsson (2003), they account for the variability of emission sources, and retention of nutrients loads that lead to uncertain final loads in coastal waters. This paper looks at risk linkages between mitigation and adaptation strategies, where mitigation strategies are measures that reduce pollutants from the emission sources (e.g. cleaning at sewage treatment plants), and adaptation strategies correspond to pollutant load changes at the water recipient (e.g. wetlands). They define risk linkage as the covariance between the remaining pollutants after mitigation and adaptation measures. The purpose of this research is to determine the risk linkage of the two measures on cost effective solutions, accounting for stochastic loads to water recipients.

They separate the Baltic Sea into individual basins; mitigation measures imply decreases in upstream emissions, and are modelled stochastic due to climate conditions. Stochastic programming is used to calculate the optimal allocation of mitigation and adaptation measures, where the problem minimises the cost for pre-specified targets. The paper assumes that the objective of the policy maker is to minimise total abatement costs for achieving a certain target. An important limitation of this study is that their method disregards the dynamics of water pollution. This we know is an important factor, since the sea takes a long time to adjust to changes in loads, this is especially true for phosphorus (which takes longer than nitrogen).

Their results show that a positive covariance between nutrient loads decreases risk, and thus total cost, while negative covariance increases it. On an international perspective, countries are assumed not to consider reductions in covariance with other countries, therefore, total abatement may exceed that of an international target. This paper demonstrates the importance of considering other countries nutrients loads to avoid over abating, which is not cost effective.

Previous literature suggests that employing nutrient reductions does not benefit all countries equally, with some countries not receiving net gains (Gren et al 1997a, Hyytiäinen et al 2013). In contrast, Gren (2003) finds that when accounting for uncertainty of the degradation of water following abatement policy of nitrogen, and hence abatement impacts following nitrogen abatement, all countries gain. Since all nine countries surrounding the Baltic Sea contribute to eutrophication, effective and efficient nitrogen reduction (marginal abatement costs are the same across the polluting countries) requires joint action.

Gren (2003) builds a model based on costs depending on the emission employed, and benefits depending on abatement in all countries. Net benefits are the maximum of the expected utility function (expected cost minus expected benefits). They use a quadratic utility function with a coefficient to measure risk aversion. This relates the expected benefits to risk (measured by variance in net benefits), and hence can be used to determine a full cooperative solution. Their results indicate that the higher the risk aversion, the lower the abatement, and the smaller the net benefits. Gren (2003) interrupts these findings to mean that although no country will lose from abatement, some countries reap substantially large benefits, motivating the possibility for redistribution schemes. A possible limitation of this study is the underestimation of benefits (benefits from biodiversity not considered), which may change the cooperative solution, possibly requiring more nitrogen abatement from all countries.

Other uncertainties from abatement policy in the Baltic Sea stems from the lack of overview in costs and benefits, and when it is appropriate to reduce only one nutrient as opposed to two. Wulff et al (2001) related the lack of reductions in nutrients to the lack of knowledge on large scale improvements. Gren (1997a) used a geographical information system (GIS) database to relate drainage basin data on nutrient loads, with the statistics of nutrient emissions for different economic sectors. The reason being that country borders do not coincide with basin borders, thus making it difficult to acquire information on the economic activities generating the loads. The purpose of the paper was to quantify the uncertain monetary costs and benefits, following a 50% nutrient reduction in nitrogen and phosphorus. Gren (1997a) finds that costs and benefits are more or less equal (benefits were

31527 million SEK annually, and costs were 31070 million SEK annually). While Elofsson (2006) found that factors like stringency of the environmental target, and the assumptions made concerning nutrient substitutability, determine the nutrient that should be reduced.

The above literature accounts for some of the uncertainties faced when considering abatement policy. Our research question requires data on costs and benefits of abatement. It is therefore beneficial to review how previous studies have gathered their data, to direct our own data collection process. Gren (1997b) uses a cost function to find cost effective nutrient reductions using prices of abatement policies. They report a lack of data on market prices for all regions, therefore, data for the Swedish Baltic Proper region is transferred to all other countries. Of course this is a limitation of the data gathering process since it assumes that all regions are the same in terms of soil and climate conditions, when in reality they could differ. Nevertheless, collecting data on costs is often difficult and the literature has to assume estimates to gather this. Gren (2001) estimates nitrogen abatement costs through econometric estimates (for sewage treatment plants, fertiliser reductions, reductions of nitrogen oxides from reduced use of gas and oil, and wetland creation). This method is also employed in Gren and Folmer (2003) and Gren (2008c). Again results are applied to all other surrounding countries.

Benefits are usually calculated using consumer valuation models and willingness to pay for improvements to the Baltic Sea (see e.g. Gren 1997a, Turner 1999, Gren and Folmer 2003). The data from consumer valuation models come directly from people's responses to hypothetical questions (e.g. would you be willing to pay X for…?). This method is often criticised for only measuring revealed preferences, not stated preferences, therefore there is a risk that responses may be an exaggeration of the true answer. Willingness to pay is often used in environmental problems to value environmental resources (the value people place, is what the resource is worth).

Although there is no literature that focuses on the time lag of benefits following abatement, it has been valuable to review literature that has considered other uncertainties to inform our own study. Likewise, the quasi option value method has not been modelled to address uncertainties in the Baltic Sea. It has however, been successfully applied to other fields of research, validating it as a good model to value important environmental concerns.

Quasi option value is used to describe the welfare gain or benefit associated with delaying a decision, when there is uncertainty about the payoffs of alternative choices, and when at least one of the choices involves the irreversible commitment of resources (Freeman 1984). This term was developed by Arrow and Fisher (1974), and later Conrad (1980) related this to the expected value of information in the presence of uncertainty. There is often a misconception between option value and quasi option value, and it is important to distinguish between the two. The concept of option value was first developed by Weisbrod (1964) and differs from quasi option value. Fisher (2000) states that option value is essentially static and related to risk aversion, and can be positive or negative. However, the quasi option value is not dependent on risk aversion, and is nonnegative. Option value is commonly used in environmental problems to value the preservation of natural resources (e.g. wilderness areas, wildlife habitats e.t.c), so they are available for future use.

Ha-Duong (1998) uses the quasi option value to address uncertainties in climate policies. They state there needs to be a balance between investment irreversibility from over cautious policy, with accelerating mitigation policy, that is bound to proceed if a worst case scenario materialises. To explore this balance, they define a quasi option value for a precautionary climate policy and relate this to the expected value of information. They consider a two stage decision process to be taken in year 2000, and long term choice to be taken in 2020. In order to implement the quasi option value model, they define two alternative policy options; one with strict abatement, and one with lower abatement remaining close to business as usual. However, this is a large assumption since in reality more than two policies are available. They assume that environmental impacts can be either high or low, and depend on a stochastic variable with probability p and $(1-p)$ of low damages. The calculation of quasi option value is determined as a proportion of opportunity cost, where they find it to be significant, amounting to 50% of the cost. Their results support large benefits in purchasing insurance against climate change by early action to mitigate greenhouse gas emissions. This study demonstrates how the quasi option value model can be effectively used to address irreversible environmental policies.

Magnan et al (2011) also uses the quasi option value in climate policy to demonstrate how no-till agriculture, a technology that delays input use, creates a quasi option value for farmers faced with the possibility of catastrophic drought. The technology allows farmers to abandon their crop in response to drought before making late season investments, thus creating a quasi option value. They distinguish between flexible and inflexible farmers, where inflexible farmers maximise net benefits with no consideration for stochastic rainfall. They calculate the quasi option value as the difference in profit between conventional tiling, and no-till agriculture for flexible farmers. They find that quasi option value makes up a large portion of the total cost saving offered by the technology.

Costello and Kolstad (2015) argue that using the quasi option value as a tax in a 'timing of extraction problem' (where extraction entails environmental damage), can stop a naïve decision maker prematurely mining before waiting for more information. They state that when environmental damage is known, the socially optimal time to mine will depend on the damage incurred, compared to the rest of the world. However, in the case of uncertain damage costs, this information is only revealed over time, motivating a mine owner to defer mining until more information is received, thus creating a quasi option value. This is a limitation of their work since they disregard any other factors that could also determine the optimal time to mine. They distinguish between a naïve and sophisticated mine owner, where the naïve owner does not account for environmental externalities (excludes social costs). They find that by imposing the quasi option value as a tax in the first period, this stops a naïve decision maker from acting too rash, they conclude this is because the cost of prematurely mining will become too high.

The literature reviewed here reiterates the importance of our research and can substantially aid in formulating our thesis. In particular, these studies clearly highlight that uncertainties regarding load reductions, and nutrient loads, extends beyond just time lag, our primary focus. It further demonstrates how different models can be used to address these areas. Reviewing how previous literature have obtained their data and understanding the constraints and limitations of this, will aid us in selecting appropriate methods and make valid assumptions when necessary. While studies using the quasi option value validate this model when applied to environmental problems. The clear approach of Ha-Duong (1998) is of particular interest to us. We too outline two polices that can be undertaken, one with strict abatement and one using low levels of abatement. Benefits will materialise in two different states of the world, where like Ha-Duong, we attach probabilities *p* and *1-p*.

3. Model Framework

The quasi option value developed by Arrow and Fisher (1974), was originally built on the premise of selecting between preserving or developing an area of natural environment. The decision to develop is irreversible, and is taken under uncertainty with regards to the associated future costs and benefits (that developing and preserving entail). The model considers two time periods; period one (now), and the period two (future). There is imperfect knowledge of future outcomes, although the decision maker has all relevant information concerning period one, period two outcomes are uncertain. At the start of period one, all possible period two outcomes can be listed with their associated probabilities. Choosing to develop or preserve is taken at the start of period one, however, it is only at the end of this period that complete knowledge about period two will be realised. Therefore, waiting until period two would provide better information.

Arrow and Fisher (1974) state that expected benefits of an irreversible decision requires adjustment, this is to account for the loss of option it causes. The size of this adjustment is the quasi option value, and thus reflects the value of delaying irreversible policy decisions until more information is known (end of period one). Consequently, this model is only relevant for situations where decisions involve uncertainty, and where at least one policy option is irreversible.

We apply this model in our thesis to value information regarding the uncertain time lag of benefits, and thus determine which state of the world we are in (one with early or late benefits). It calculates the expected payoff from waiting to obtain more information, before enforcing a high and expensive abatement policy, which we argue is irreversible.

We could employ other methods to calculate the value of information. Lave (1963) related the quantity of raisins to the number of degree days using regression analysis (how much crop can be dried before rain), to determine the effects of better weather information to Californian raisin growers. If we too followed this method, it would allow us to capture the causal relationship between benefits and abatement policy. Benefits become the dependent variable, while abatement policy is the independent variable. A dummy variable to indicate if there is high or low abatement policy, along with a dummy variable to capture early or late benefits could be used. Nevertheless, there are numerous explanatory variables we must account for to avoid causing bias in the regression, these cannot all be quantified and kept constant.

Bayesian networks are also a method that is being used to calculate value of information, it involves determining the relationship among important variables in a system of interest (Borsuk 2004). The variables are represented by nodes, where arrows are used to show conditional probability, highlighting the relationship among the variables. In terms of the Baltic Sea, it is difficult to determine the most important variables that affect the distribution of early and late benefits. This method cannot be applied in this thesis, since we must identify the most dominant variables that affect large and small abatement policy, and the corresponding effects on benefits. There are a lot of variables (see section 2) that affect this, and are hard to measure and assign probabilities to. Furthermore, this model cannot consider changing policy after period one, where a low abatement policy can be followed by a large one. Therefore, we argue that the quasi option value is the most appropriate method to use.

3.1 Application of Model

We focus solely on nitrogen abatement and define two abatement policies that can be undertaken by all nine bordering countries, under two time periods. The first involves a high level of abatement, which is considered to be irreversible, we label this A+. If this policy is selected in period one, period two must also incorporate this policy. Whereas, policy A- is a low level of abatement and if selected in period one, can be changed to a higher level of abatement in period two. We assume we are at the start of period one, and must make a decision between the two policies, where information on the uncertain time lag of benefits is attained at the end of this period (Figure 2).

The quasi option value method is limited to assuming only two policy options, this is of course a disadvantage of the model, since in reality policy makers have a choice between multiple decisions. However, to keep our model simple we can only account for high and low abatement. Furthermore, this model requires analysing the outcomes of these policies over only two time periods (now and future), again this is a limitation and abstracts away from reality, where there can be multiple time periods to analyse policy. However, this would make the calculations far too complicated, and execution not practical if more than two time periods are considered. Therefore, for feasibility we should make this assumption.

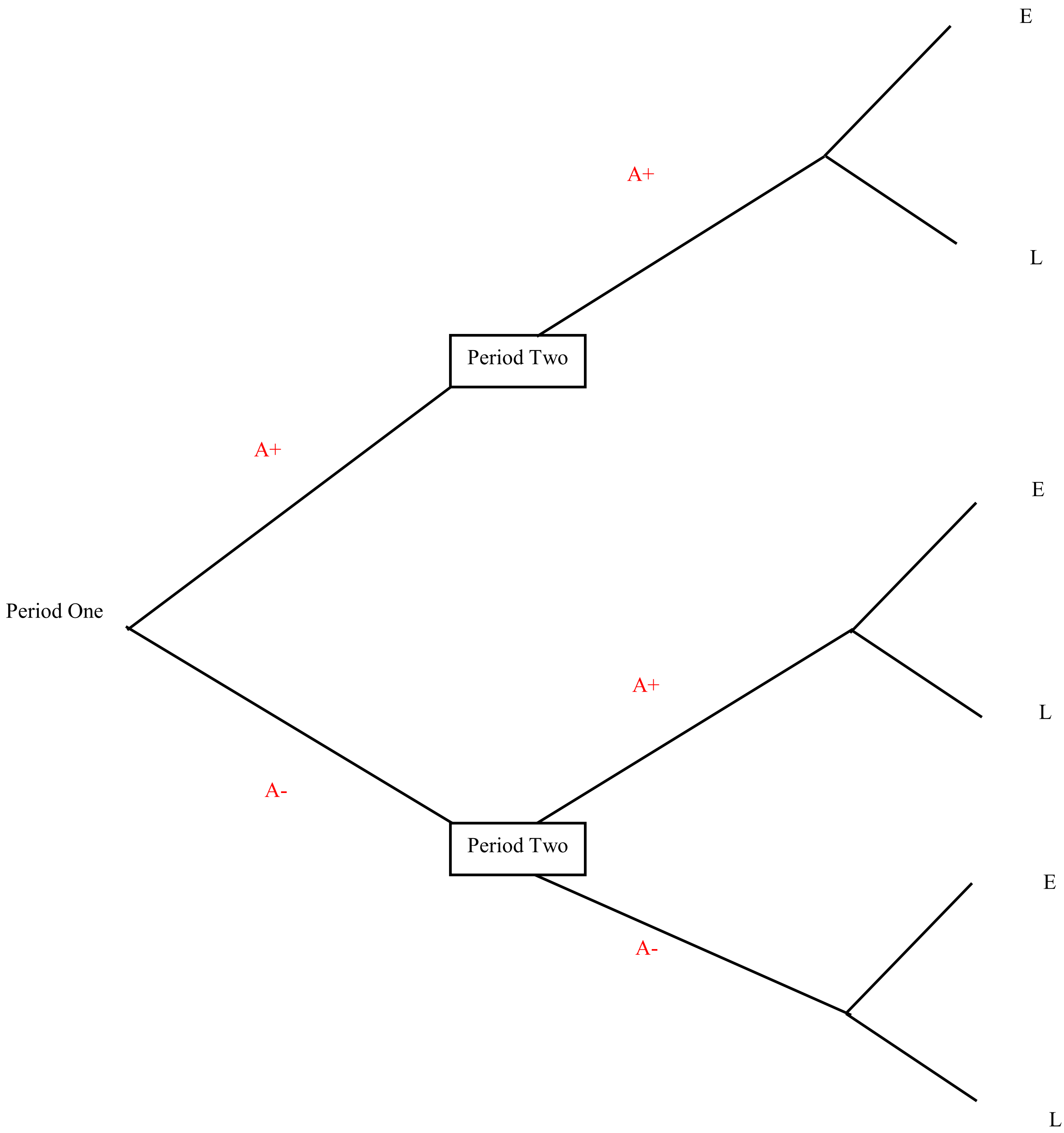

Figure 2. Decision tree showing all combinations of policy options available and corresponding outcomes in the two states of the world that could materialise.
A+, high abatement; A-, low abatement; E, early benefit; L, late benefit.

3.2 Calculation of the Quasi Option Value

To determine the quasi option value, we calculate the expected and expectation value of net benefits from high and low abatement. The difference between the expectation and expected value is the quasi option value. This reflects the value of information to eliminate the uncertainty of time lag of benefits. All strategies enforced have their own unique return associated with the investment (Table 1).

Table 1. Combination of possible strategies and associated returns.

Policy Option	Period One	Period Two	Return
1	A+	A+	$R^{A++} = B_1^{A+} - C_1^{A+} + (B_2^{A++} - C_2^{A++})$
2	A-	A-	$R^{A--} = B_1^{A-} - C_1^{A-} + (B_2^{A--} - C_2^{A--})$
3	A-	A+	$R^{A-+} = B_1^{A-} - C_1^{A-} + (B_2^{A-+} - C_2^{A-+})$

B_1^{A+}*, benefit of strategy A+ in period one*
C_1^{A+}*, cost of strategy A+ is period one*
$B_2^{A++} - C_2^{A++}$*, net benefit of strategy A++ in period two*
B_1^{A-}*, benefit of strategy A- in period one,*
C_1^{A-}*, cost of strategy A- in period one*
$B_2^{A--} - C_2^{A--}$*, net benefit of strategy A-- in period two*
$B_2^{A-+} - C_2^{A-+}$*, net benefit of strategy A-+ in period two*

Note from Table 1, that the net benefit of strategy A- in period one ($B_1^{A-} - C_1^{A-}$) is common to both policy two and three. The return to the decision maker in period one from enforcing strategy A- is R^{A--} or R^{A-+}, depending on whether or not a large abatement is initiated in period two, given the information then available. If the net benefit of strategy A-- is higher than A-+ ($R^{A--} > R^{A-+}$), then the decision maker will enforce this policy (vice versa).

The benefits of following strategy A++ is simply as shown in Equation 1, and Table 1.

$$R^{A++} = (B_1^{A+} - C_1^{A+}) + (B_2^{A++} - C_2^{A++}) \qquad \textbf{[1]}$$

The benefit of following strategy A- is Equation 2, depending on which policy is enforced in period two. The ‘Max’ is short for whichever is the largest term in the brackets to be selected.

$$R^{A-} = (B_1^{A-} - C_1^{A-}) + Max[(B_2^{A--} - C_2^{A--}), (B_2^{A-+} - C_2^{A-+})] \quad \textbf{[2]}$$

If we assume that the decision maker has complete knowledge for the relevant future circumstances, hence all future costs and benefits are known, then the decision maker will also know R^{A++}, R^{A--} ,and R^{A-+}. The decision maker will enforce strategy A++ if $R^{A++} > Max[R^{A--}, R^{A-+}]$. Using Equation 1 and 2, we can construct the following Equation 3. This states that strategy A++ will be followed as long as $R^{A++} - Max[R^{A--}, R^{A-+}] > 0$

$$(B_1^{A+} - C_1^{A+}) + (B_2^{A++} - C_2^{A++}) - (B_1^{A-} - C_1^{A-}) - Max[(B_2^{A--} - C_2^{A--}), (B_2^{A-+} - C_2^{A-+})] > 0$$

[3]

However, we know that Equation 3 cannot be known to the decision maker at the start of period one, due to the uncertain outcome of period two. Instead, we assume outcomes may be known to the decision maker, where he or she can attach probabilities to these mutually exclusive events. It is therefore intuitive to replace Equation 3 with the corresponding expected values and expectations. Equation 4 uses the expected values.

$$(B_1^{A+} - C_1^{A+}) + E(B_2^{A++} - C_2^{A++}) - (B_1^{A-} - C_1^{A-}) - Max\{E[(B_2^{A--} - C_2^{A--})], E[(B_2^{A-+} - C_2^{A-+})]\} > 0$$

[4]

Although Equation 4 takes into account that outcomes are not in fact known to the decision maker at the start of period one (unlike Equation 3), it still disregards the fact that more information will become available in period two. If a high level of abatement is selected in period one, then the new information cannot be used. Taking the expectation of Equation 3 does take this into account, this is shown in Equation 5.

$$(B_1^{A+} - C_1^{A+}) + E(B_2^{A++} - C_2^{A++}) - (B_1^{A-} - C_1^{A-}) - E[Max\{(B_2^{A--} - C_2^{A--}), (B_2^{A-+} - C_2^{A-+})\}] > 0$$

[5]

The difference between Equation 5 and 4 is simply the quasi option value, note $(B_1^{A+} - C_1^{A+}) + E(B_2^{A++} - C_2^{A++}) - (B_1^{A-} - C_1^{A-})$ is common to both equations so this can cancel out, as shown in Equation 6.

$$E[Max\{(B_2^{A--} - C_2^{A--}), (B_2^{A-+} - C_2^{A-+})\}] - Max\{E[(B_2^{A--} - C_2^{A--})], E[(B_2^{A-+} - C_2^{A-+})]\}$$
[6]

We assume two possible period two scenarios. State one is that benefits are received early (with probability *p*), while the second state is that benefits are delayed (with probability (*1-p*)). We need to calculate Equation 4 and 5 for these two states

Equation 4a states under what condition strategy A++ will be taken, using expected values to calculate the benefits under each strategy. $XB_2^{A++}$is equal to the early benefits of strategy A++ in period two, LB_2^{A++} is late benefits of strategy A++. It follows that XB_2^{A--} is early benefits of strategy A-- in period two, LB_2^{A--} is late benefits of strategy A--. Finally, XB_2^{A-+} is the early benefits of strategy A-+ in period two, while LB_2^{A-+}late benefits of strategy A-+ in period two. Equation 5a states under what condition strategy A++ will be taken using expectations.

$$(B_1^{A+} - C_1^{A+}) - (B_1^{A-} - C_1^{A-}) + \left(p(XB_2^{A++} - C_2^{A++}) + (1-p)(LB_2^{A++} - C_2^{A++})\right) - Max\{[p(XB_2^{A--} - C_2^{A--}) + (1-p)(LB_2^{A--} - C_2^{A--})], [p(XB_2^{A-+} - C_2^{A-+}) + (1-p)(LB_2^{A-+} - C_2^{A-+})]\} > 0$$
[4a]

$$(B_1^{A+} - C_1^{A+}) - (B_1^{A-} - C_1^{A-}) + \left(p(XB_2^{A++} - C_2^{A++}) + (1-p)((LB_2^{A++} - C_2^{A++})\right) - \{p[Max(XB_2^{A--} - C_2^{A--}), (LB_2^{A--} - C_2^{A--})] + (1-p)[Max(XB_2^{A-+} - C_2^{A-+}), (LB_2^{A-+} - C_2^{A-+})]\} > 0$$
[5a]

Subtracting Equation 4a from 5a will give us the quasi option value, leading to Equation 6a. This is the quasi option value, and what we want to calculate for the net benefits of nitrogen reduction.

$$p[Max(XB_2^{A--} - C_2^{A--}),(LB_2^{A--} - C_2^{A--})] + (1-p)\ [Max(XB_2^{A-+} - C_2^{A-+}), (LB_2^{A-+} - C_2^{A-+})] - \ Max\{[p(XB_2^{A--} - C_2^{A--}) + (1-p)(LB_2^{A--} - C_2^{A--})],[p(XB_2^{A-+} - C_2^{A-+}) + (1-p)(LB_2^{A-+} - C_2^{A-+})]\}$$

[6a]

3.3 Assumptions About Timing of Policy

We motivate the selection of time periods in terms of irreversibility of policy options. Pommeret and Prieur (2009) investigate the role of irreversibility in environmental policy. They state irreversibility takes two forms, one relates to the actual degradation of the environment, and the other to the sunk cost of environmental policy. In terms of the Baltic Sea, selecting a low abatement policy may mean irreversible damage to the sea (or requires a very long time to fix). However, enforcing a high abatement policy is expensive, and the cost incurred here is sunk.

We therefore assume that strategy A+ is irreversible, if this decision is made in period one, period two must enforce this policy as well. It cannot be revoked in the case more information comes to light, or conditions change. We relate this to the idea of the sunk cost of environmental policy. It would be logical to assume that enforcing a policy where a large abatement is required, would involve more investment in abatement technology than a less ambitious policy. As a result, the actual investment in technologies make the policy irreversible, since it would simply be too costly to change. Policy makers are therefore reluctant to change to a lower abatement strategy once they have invested sufficiently in high abatement. Policy A- requires a low level of abatement, hence lower investment, we assume after period one, we can in fact change strategies and implement A+.

We will use 25 years for each time period (and assume we are at the start of period one), where period one is from 1991 to 2015, while period two will run from 2016 to 2040. We further assume that early and late benefits can materialise with equal probability.

3.4 Timing of Early and Late Benefits

We relate benefits to the expected time taken for concentration levels to decrease following abatement. Hence, when levels decrease, benefits will increase.

Savchuk and Wulff (2007) model the response of concentration levels in the Baltic Sea after full abatement of nitrogen and phosphorus. They find that concentration levels of nitrogen take 20 years to reach a steady state. On the other hand, the response of dissolved inorganic nitrogen (sum of nitrate and ammonia) is much slower. Concentration levels are reported to follow a convex shape at the beginning, it is only after 20 to 30 years any form of reduction in concentration levels are seen. Stålnacke et al (2003) explore the decrease in fertiliser, extensive slaughtering of livestock, and reduced amount of manure use in Estonia, Latvia, and Lithuania between 1987 and 1996. They measure the impact this reduction has on the concentrations of nutrients in Latvian rivers. Their results show that in the majority of basins examined, no statistically significant decrease (of nitrogen concentrations) is seen during 1987 and 1988.

The combination of nitrogen and dissolved inorganic nitrogen from different sources are not well known, therefore, it is difficult to accurately determine the timing of benefits. We will use the two studies above to build our assumptions of time lag benefits.

Assumption one: early benefits start after year 10. This is based on Stålnacke et al (2003) not observing a decrease in nitrogen concentration levels for the duration of their 10 year study.

Assumption two*:* it takes 10 years to reach a steady benefit level. This is based on Stålnacke et al's (2003) lack of observations of decreases in concentration levels for the duration of their 10 year study, and Savchuk and Wulff (2007) observing a steady level of concentrations by year 20.

During this 10 year period from when benefits first arise to when they reach a steady level, there will be a linear increase.

Assumption three: late benefits start in year 25 (and reach steady level by year 35). We relate this to the time taken for dissolved inorganic nitrogen concentrations to decrease, as reported in Savchuk and Wulff (2007).

Recall that period one and two both consist of 25 year time periods, meaning the costs of abatement are incurred over a 50 year horizon. However, the distribution of benefits exceeds this time horizon. We assume that a 25 year abatement policy will entail benefits for 25 years. Table 2 summarises the distribution of costs and benefits expected for each policy, under both early and late benefits.

Figure 3 illustrates the progression of early and late benefits for policy A++. The early benefits are represented by the blue line, and late benefits by the red. Early benefits start after year 10 (2000) and progress linearly to the stable level of A+ benefits in year 20 (2010). In period two (2016) where the same policy is initiated, this continues the steady levels of benefits for an additional 25 years (2060). After this point, (when there is no more benefits from abatement) benefits begin to decrease back to zero, we assume this occurs at the same rate they increased, therefore taking 10 years to reach zero benefits. This is seen in year 70 (2060). Late benefits on the other hand start after year 25 (2015), they too take 10 years to reach the steady level of benefits A+. In this scenario, the high abatement strategy enforced in period two (2016), only materialises after 25 years (year 50 (2040)), thereby continuing the steady level of benefits until year 75 (2065). Again, once all benefits from abatement are reaped, they fall back to zero (by year 85 (2075)).

Table 2. Distribution of costs and early/late benefits for all policies. Early benefits start after 10 years of abating and last for 25 years. Late benefits arrive after 25 years of abating and last for 25 years.

	Policy	Time Period	Costs	Benefits
Early Benefits	**A++**	1	Year 1-25 (1991-2015)	Year 11-35 at A+ (2001-2025)
		2	Year 26-50 (2016-2040)	Year 36-60 at A+ (2026- 2050)
	A--	1	Year 1-25 (1991-2015)	Year 11-35 at A- (2001-2025)
		2	Year 26-50 (2016-2040)	Year 36-60 at A- (2026- 2050)
	A-+	1	Year 1-25 (1991-2015)	Year 11-35 at A- (2001-2025)
		2	Year 26-50 (2016-2040)	Year 36-60 at A+ (2026-2050)
Late Benefits	**A++**	1	Year 1-25 (1991-2015)	Year 26-50 at A+ (2016-2040)
		2	Year 26-50 (2016-2040)	Year 51-75 at A+ (2041-2065)
	A--	1	Year 1-25 (1991-2015)	Year 26-50 at A- (2016-2040)
		2	Year 26-50 (2016-2040)	Year 51-75 at A- (2041-2065)
	A-+	1	Year 1-25 (1991-2015)	Year 26-50 at A- (2016-2040)
		2	Year 26-50 (2016-2040)	Year 51-75 at A+ (2041-2065)

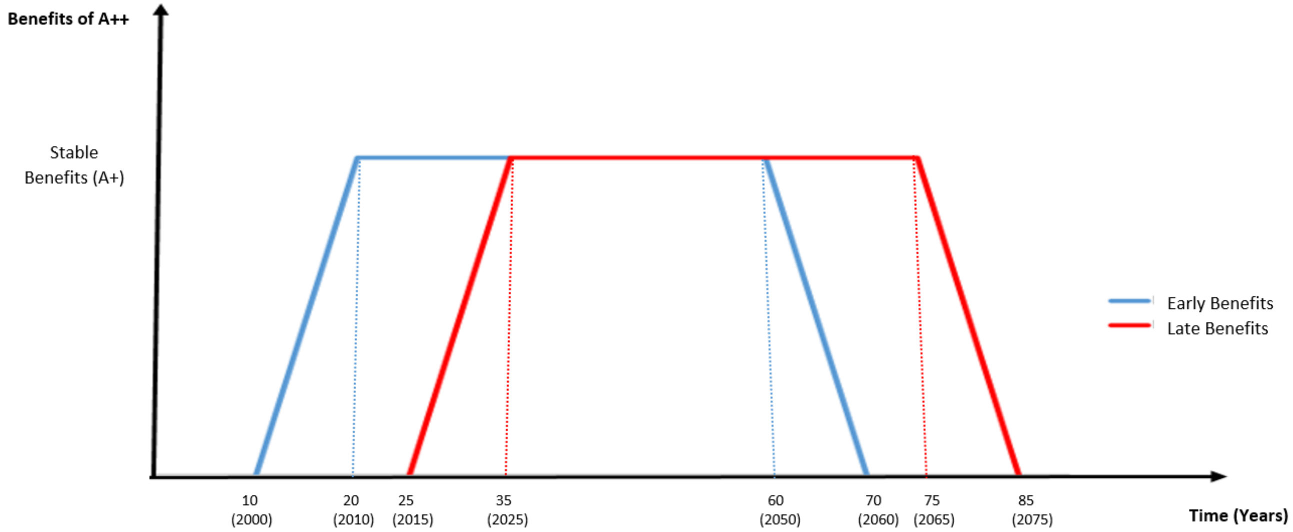

Figure 3. Progression of early and late benefits for policy option A++.

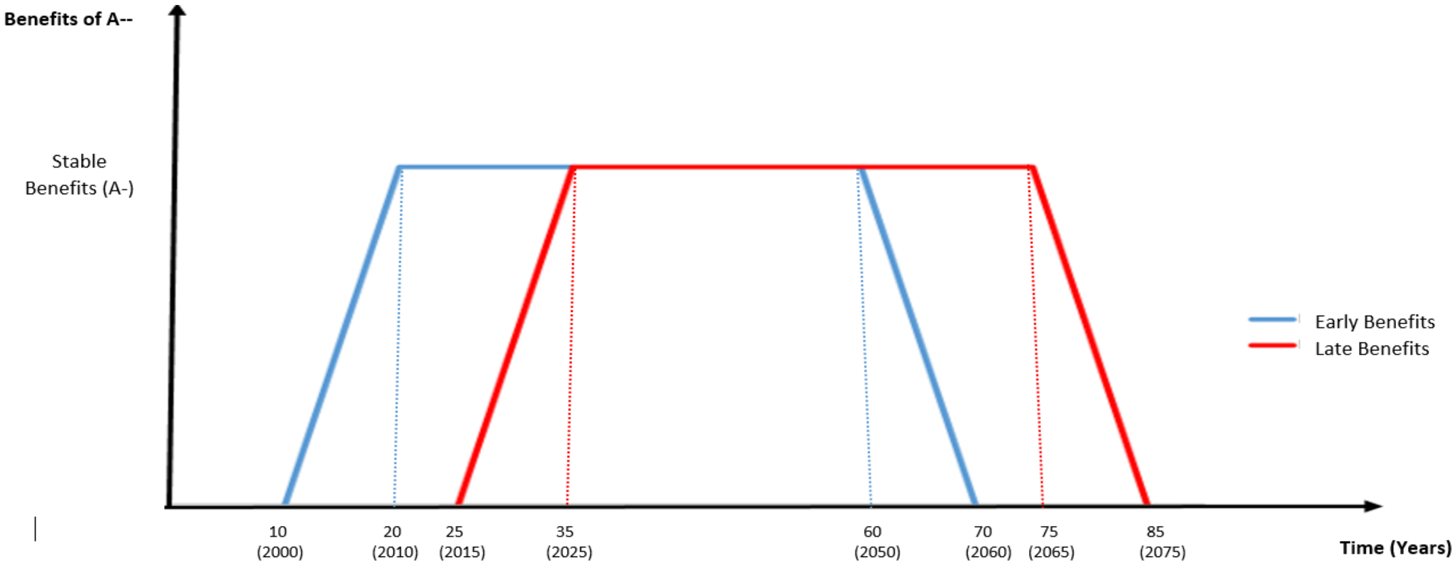

Figure 4. Progression of early and late benefits for policy option A--.

Figure 4 illustrates the evolution of early and late benefits under policy A--, notice it mirrors the distribution of Figure 3. However, only the stable level of A- benefits is reached, naturally, this is much lower than A+ benefits.

Figure 5 shows the progression of early and late benefits following abatement policy A-+, the blue line corresponding to early benefits, and the red to late benefits. Again early benefits materialise after year 10 (2000), and reach a steady benefit level by year 20 (2020). However, now a high abatement policy is initiated in period two (2016), taking 10 years to materialise. This is shown in Figure 5 by the upward sloping line after year 35 (2025). After this point a new higher A+ steady level benefit is reached, this continues until year 60 (2050), before falling back to zero in year 70 (2060), once all benefits are obtained. Late benefits follow the same distribution as early benefits, with the late benefit curve simply shifted to the right. Benefits start after year 25 (2015) and reach a steady A- benefit in year 35 (2025). The high abatement strategy enforced in period two does not materialise until year 50 (2040). Stable A+ benefits are now reached in year 60 (2050).

It is important to note the benefits we will achieve in our calculations are largely affected by the timing of early and late benefits we assume. As a result, the quasi option value we find will also be sensitive to changes in the expectation, of when these benefits are likely to materialise. This is of course a limitation of this process. However, we have conducted an extensive literature search, and tired our best to base the timing of early and late benefits on the literature and evidence available.

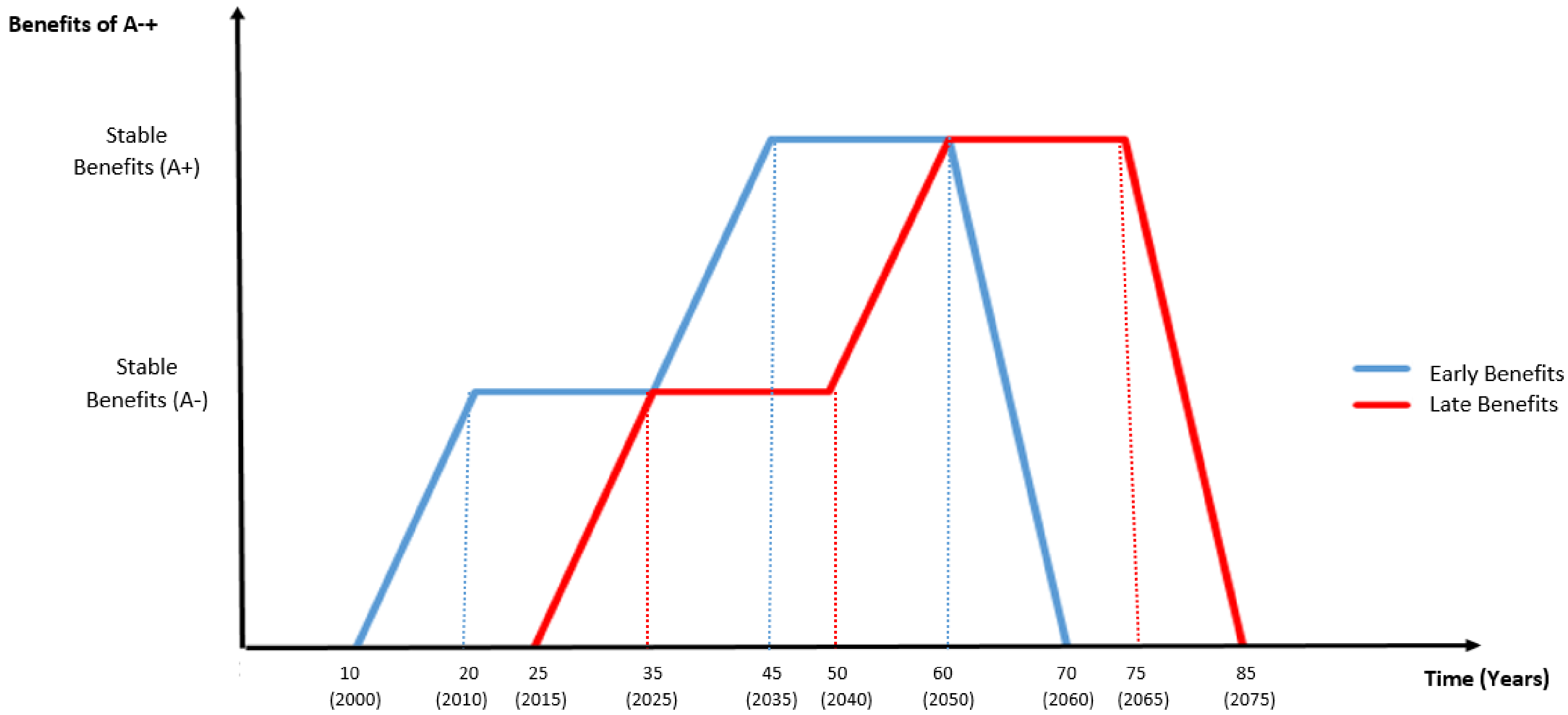

Figure 5. Progression of early and late benefits for policy

4. Methods and Applications

This section will explain how we will collect and calculate the costs and benefits following abatement of nitrogen.

4.1 Data

We assume that strategy A+ is one where all countries comply with the BSAP, which can be found on the HELCOM homepage, and shown in Table 3. This is the proposed country allocated reduction targets set. On the other hand, strategy A- are the actual reductions according to HELCOM PLC5 (HELCOM 2011), and are also presented in table 3. This displays the difference in emissions, hence reductions made between 2006-2008 and 1997-2003.

Table 3. Country allocated reductions according to HELCOM and actual reductions according to HELCOM PLC5 (Pollution Load Compilation 5, ch 5, flow normalised annual reductions: difference 2006-2008 to 1997-2003). Source: helcom.fi, HELCOM (2011).

Country	BSAP Nitrogen Reduction Targets (tonnes)	Actual Reduction of Nitrogen (tonnes)
Denmark	17,210	12,138
Estonia	900	-5,790
Finland	1,200	-5,635
Germany	5,620	635
Latvia	2,560	-18,167
Lithuania	11,750	6,085
Poland	62,400	-2,187
Russia	6,970	-5,374
Sweden	20,780	5,247

To obtain data on costs we will use a cost function from Elofsson (2006), which calculates the cost of abatement using reductions employed, separately for each nine bordering countries. We insert the required reductions as shown in Table 3 into the cost function, and achieve costs for all years from 1991 until 2040. Some of the actual reductions taken as shown in Table 3 column 3, are recorded with minus, this is simply because these countries have failed to reduce loads (between 2006-2008 and 1997-2003). Therefore, we will record their reductions as zero in the cost function. This will mean these countries do not entail any costs from abatement, since they have not abated. We do not consider that these countries may have in fact abated, but possible growth in their markets has led to an increase in the demand for nitrogen.

To collect data on benefits, we assume a downward sloping demand curve for nitrogen reduction. By employing a method used in Gren et al (2009), and taking elasticity of nitrogen reduction from Hökby and Söderqvist (2003), we integrate the demand curve to give us the associated consumer surplus. A consumer surplus arises when there is a difference between the price that consumers are willing to pay in the market (hence the value placed on the product by the consumer), and the actual price. This is an economic measure of satisfaction and calculates the welfare gain from consuming the good. Therefore, this corresponds to the annual aggregate benefits from abatement.

4.2 Calculation of Costs

The cost function we use is; $\ln C_{ri}\ (e_{ri}) = \beta_1 + \beta_2 \ln(e_{ri}^0 - e_{ri})$ (Elofsson 2006), where C_{ri} is equal to costs (expressed in million SEK) and e_{ri}^0 is equal to initial emissions, while e_{ri} are current emissions. Therefore, $e_{ri}^0 - e_{ri}$ is equal to the reductions employed (which will be taken from Table 3). Elofsson (2006) further defines quantities for β_1 and β_2 unique for each country as shown in Table 4. By inserting these parameters into the cost function, we will obtain separate costs for each country. We assume the costs incurred are the same every year (from 1991 until 2040). To account for the time value of money, we discount back to the start of period one (1991). We can then aggregate the costs of all countries in each time period and convert into euros using 1 SEK= 0.11 EUR, correct as of 12/04/16.

The assumption that costs are the same in every period disregards the fact that costs may in fact decrease over time, due knowledge diffusion and technological innovation. Generally, costs decrease over time, the rate at which they decrease however, depends on the innovation of technology and how this relates back to abatement costs. This is difficult to measure and incorporate, therefore, we believe our assumption is valid.

Table 4. Coefficients of cost function.
Source: Elofsson (2006).

Country	Denmark	Estonia	Finland	Germany	Latvia	Lithuania	Poland	Russia	Sweden
β_1	-15.190	-13.889	-16.092	-12.507	-18.007	-17.807	-18.433	-4.804	-11.940
β_2	2.395	2.192	2.380	2.167	2.580	2.579	2.460	1.155	1.896

4.3 Calculation of Benefits

We need to formulate a benefit function in order to measure the gain from abatement. Gren et al (2009) uses an inverse demand function to calculate the control costs of decreases in emissions from reductions in energy users. They determine this by integrating the demand curve to find the change in consumer surplus (which is equal to benefits), following deviations from 'business as usual' points (costs are calculated as associated decreases in consumer surplus).

Figure 6 shows a downward sloping demand curve for nitrogen reduction which is equal to the marginal benefits from abatement. The marginal benefits of abatement are subject to diminishing returns, this simply means that abating one more unit while holding everything else constant, will yield a lower benefit than the last unit. This is the reason we have a downward sloping marginal benefit curve. The marginal cost curve is upward sloping since we know that the more units we abate, the more expensive this will be. In environmental problems, it may seem that abating fully is optimal, however this is not the case. After a certain point, the marginal cost of reducing the pollutant exceeds the marginal benefit (Buchanan 1965). Instead an equilibrium is reached when marginal costs are equal to marginal benefits (Buchanan 1965). Consequently, Figure 6 shows that optimal abatement quantity is point A*

We make the assumption that when HELCOM designed the BSAP (Table 3 column 2), they in fact equated the marginal costs and benefits from abatement to decide the load reductions to set. Thus point A* in Figure 6 corresponds to the aggregate nitrogen reductions of the BSAP (hence strategy A+). Of course there is a limitation to this assumption, although economically speaking it is correct to determine load reductions in this manner, in reality this method is not employed. HELCOM determines load reductions by estimating the maximum allowable inputs of nutrients to reach the eutrophication target of clear water, they do this using SANDBALT (model developed by MARE research program in Sweden). These maximum allowable targets and are then used in combination with agreed allocation principles to determine the load reductions.

Marginal costs are calculated by differentiating our cost function, which corresponds to the point P_{A*} in Figure 6. Hökby and Söderqvist (2003) look at the demand function for nitrogen reduction, they find that the price elasticity of demand for nitrogen reductions is -1.86, i.e. demand is relatively elastic, implying a slow decrease in marginal benefits. Using all these points will allow us to follow the method used in Gren et al (2009) to calculate our benefits.

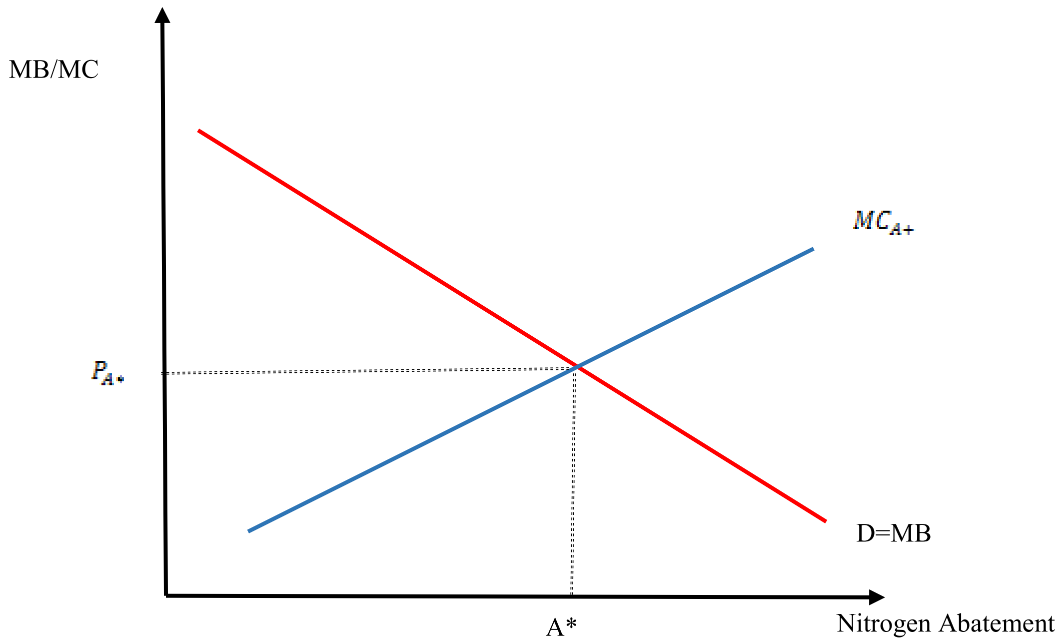

Figure 6. Marginal benefit (MB) and marginal cost (MC) curve of nitrogen abatement.

Equation 7 is the marginal cost function and derived from the cost function we are using. Please refer to Appendix 1 for full calculations. The country with the highest marginal costs will be used as the point P_{A*}. This is simply because the benefits we are calculating are on an aggregate level, therefore, in order to abate marginal cost cannot be higher than marginal benefit, we must use the country with the highest marginal cost to ensure there is abatement.

$$\frac{\partial C_{ri}(e_{ri})}{\partial Q_{ri}} = \beta_2 K Q_{ri}^{\beta_2 - 1} \quad \textbf{[7]}, \qquad \text{where } K = e^{\beta_1}$$

Equation 8 shows the benefit function we calculate, where X_{ijh} refers to the quantity abated and a_{ijh} and b_{ijh} are coefficients of interest. Please refer to Appendix 2 for complete calculations for deriving the benefit function.

$$\frac{a_{ijh}}{b_{ijh}} X_{ijh} - \frac{X_{ijh}^2}{2b_{ijh}} + C \quad \textbf{[8]}$$

By inserting the quantity abated into the Equation 8 (X_{ijh}), we achieve the corresponding annual stable benefit. We assume these benefits are the same every year. Therefore, we must discount benefits after 1991 back to the start of period one (1991). This is the aggregated benefits, and hence calculates the benefits of abatement for all nine countries. A limitation of this method is that we cannot determine which country gains the most benefit from abating, it is very unlikely that benefits are distributed equally across countries.

In addition to this, the benefits we achieve by inserting abatement into Equation 8, corresponds to the stable benefits (as seen by the flat lines in Figures 3, 4, and 5). However, we will assume that benefits received prior to the steady level change linearly, as shown in the upward sloping lines in Figures 3, 4, and 5 (between year 10 and 20 for early benefits, and year 25 and 35 for late benefits). Please see Appendix 2.1 for an explanation of calculations.

4.4 Discounting Costs and Benefits

Since we are assuming we are at the start of period one (1991), costs and benefits after this date are a future value and must be discounted back to the present value. To do this we simply need to use the formula below. Costs and benefits in each year are discounted separately before they are aggregated and converted into EUR.

$$PV = FV * (1 + i)^{-t}$$

Where PV, present value; FV, future value; i, discount rate; t, time (year).

4.4.1 Selecting a Discount Rate

Discounting takes into account the time perspective of money and the opportunity cost of the resources used in a project. People tend to value consumption today more than in the future. This is because of the pure time preference, for example, the same amount of money today is worth more than in the future, due to its capacity to earn interest. This leads to an opportunity cost of spending money now. The value the discount rate should be set at is a controversial matter, setting a positive discount rate values the future less than today, the higher this rate is, the lower the value placed. Hence, a positive discount rate would mean the value of future benefit streams is reduced compared to the same benefit in present time. Only a discount rate of zero would mean equal value being assigned to the future and present. The choice of discount rate will influence our values of costs and benefits, and hence the quasi option value (the larger the discount rate employed, the lower the future costs and benefits).

Generally, the Ramsey formula is used to determine the discount rate to use, it relates the discount rate to the growth rate of consumption, as shown below.

$$r = \rho + \eta g$$

Where r, discount rate; ρ, utility discount rate (pure time preference); η, elasticity of marginal utility w.r.t. to consumption; g, growth rate of consumption.

It is sometimes recommended that environmental policy should be discounted using the rate employed in the Stern Review. This was a report conducted on the economics of climate change using a rate of 2.1% with $\rho = 0.1\%$, $\eta = 1$, and $g = 2\%$ (Nordhaus 2007). However, this can be criticised for being too low. Lindqvist et al (2013) uses a discount rate of 3% to analyse the impact of technical change through learning by doing in the Baltic Sea.

The British Treasury (HM Treasury 2003) also advices that projects between 31 and 75 years should employ a 3% discount rate. Therefore, we will use 3%.

The selection of the discount rate is generally considered an ethical issue since we are valuing the future. By implementing a positive discount rate, we are in fact valuing the future less than the present (the higher the rate the lower the value placed). Some economists argue that a zero discount rate should be used. There is a large body of literature that contributes to this ethical issue, Groom et al (2005) looks at the idea of inter-generational equity. The present generation have a moral obligation to protect future generations, since they cannot express their preferences. Therefore, a precautionary principle should be enforced. Nordhaus (2007) argues that future generations should be able to make the same choices as present generations. To account for this, I will conduct sensitivity analysis to determine how the quasi option value changes using a discount rate of zero.

5. Results

We will now present the results of our method starting with the discounted aggregated costs, followed by discounted aggregated benefits, and finally the calculation of the quasi option value.

5.1 Results of Aggregated Costs

The costs of all three policy options in both time periods are displayed in Table 5 and 6. Table 5 shows to abate the level A+, it would cost all nine countries a combined amount of 23.7 billion EUR during 1991-2015. Denmark and Poland take on the largest costs, since they are allocated to reduce the most. In the time period 2016-2040, to continue enforcing strategy A+, it will cost 11.3 billion EUR.

Table 5. Discounted aggregated country costs of strategy A++ in EUR (1991-2015 and 2016-2040).

Country	Discounted Aggregate Costs 1991-2015	Discounted Aggregate Costs 2016-2040
Denmark	6,964,167,335	3,326,125,104
Estonia	5,481,390	2,617,942
Finland	4,314,115	2,060,446
Germany	975,134,909	465,729,863
Latvia	18,536,408	8,853,091
Lithuania	1,143,544,349	546,163,150
Poland	12,187,400,950	5,820,770,569
Russia	444,314,372	212,207,018
Sweden	1,976,455,449	943,966,130
Total Cost	**23,719,349,276**	**11,328,493,314**

Table 6 shows the cost for implementing abatement under policy A-- and A-+. We can see in period one, the cost of initiating low abatement is 3.4 billion EUR, with Denmark taking the highest cost burden. Some countries are recorded as having zero costs (Estonia, Finland, Latvia, Poland and Russia), this is simply because these countries do not abate under strategy A-, and therefore do not incur costs. If this same policy is continued in period two, it would entail a cost of 1.6 billion EUR. However, if in period two the policy maker decides to start abating a high level, this would increase costs to 11.3 billion EUR.

Table 6. Discounted aggregated country costs of strategy A--and A-+in EURS (1991-2015 and 2016-2040).

Country	Discounted Aggregate Costs 1991-2015 (A-)	Discounted Aggregate Costs 2016-2040 (A-)	Discounted Aggregate Costs 2016-2040 (A+)
Denmark	3,017,910,786	1,441,370,999	3,326,125,104
Estonia	0	0	2,617,942
Finland	0	0	2,060,446
Germany	8,649,615	4,131,104	465,729,863
Latvia	0	0	8,853,091
Lithuania	209,523,817	100,069,742	546,163,150
Poland	0	0	5,820,770,569
Russia	0	0	212,207,018
Sweden	145,406,043	69,446,736	943,966,130
Total Cost	**3,381,490,261**	**1,615,018,581**	**11,328,493,314**

Period two costs of A++ and A-+ are the same. This is because we have assumed there are no gains to be reaped from enforcing a higher level of abatement in period one (in terms of A++). Thus, the cost of policies is not affected by previous policies installed. It can be argued this assumption may be flawed since having a high abatement policy in period one should entail some cost benefits for the next period, e.g. in terms of technological innovation and learning by doing. However, it is difficult to determine how these benefits are translated to a decrease in costs.

5.2 Results of Aggregated Benefits

Recall from Figure 6 that a cost effective solution requires equating the marginal cost and marginal benefit. The corresponding X-axis value is the quantity, and in our case the quantity abated, while the Y-axis is the price. We assumed the A* was the amount advised by HELCOM in the BSAP, this is simply 129,390 tonnes of nitrogen (summing up column 2 of Table 3).

We calculated the marginal cost function as Equation 7 (see Appendix 1). We simply enter the parameters from Table 3 and 4 into this function to achieved marginal costs for each country in EUR.

Table 7. Marginal cost of strategy A+ in EUR.

Country	Denmark	Estonia	Finland	Germany	Latvia	Lithuania	Poland	Russia	Sweden
Marginal Cost	54,036	744	477	20,964	1,042	13,994	26,788	4,105	10,055

As we can see from Table 7, the highest marginal cost of abatement belongs to Denmark, therefore, we will use this marginal cost to formulate our benefit function (corresponding to the point on Y-axis on Figure 6). Recall from section 4.3, that we must use the country with the highest marginal cost, since our benefit function is considered on an aggregate level, and so abatement is considered on an aggregate level (for all nine countries including Denmark to abate, marginal cost cannot be higher than marginal benefit). We are now in a position to integrate the demand curve for nitrogen reduction, to find the corresponding benefits of abatement.

Our benefit function was simply Equation 8. Please see Equations A9 and A10 in Appendix 2 for calculating a_{ijh} and b_{ijh}. By inserting the load reductions made, we find the corresponding benefits. Our calculations show that a_{ijh} = 370055.4 and b_{ijh} $=$0.489922071.

Policy A+: we insert $X_{ijh} =$ 129,390 (summing column 2 of Table 3). This gives us the aggregated annual benefits of 8.9 billion EUR. This is the expected stable annual benefit that should be achieved by all nine countries combined if policy A+ is used.

Policy A-: we insert $X_{ijh} =$ 24,105 (summing reductions from column 3 of Table 3). This gives us the aggregated annual benefits of 1.9 billion EUR. This is the stable expected annual benefit that should be achieved by all nine countries if policy A- is used.

Recall that we assumed a linear relationship while benefits were increasing. We assumed it takes 10 years to reach a stable level of benefits, this we refer to as increasing benefits. We also assumed it takes 10 years for benefits to reach zero once stable benefits have stopped, this we refer to as decreasing benefits. Table 8 shows the expected benefits from increasing and decreasing benefits in EUR (without discounting). Note that the two types of benefits are simply in reverse. This is because we assume benefits increase and decrease at the same rate.

Table 8. Increasing and decreasing benefits of A+ and A- in EUR.

Policy	Increasing		Decreasing	
Year	A+	A-	A+	A-
0	0	0	8,871,133,370	1,937,578,739
1	887,113,337	193,757,874	7,984,020,033	1,743,820,865
2	1,774,226,674	387,515,748	7,096,906,696	1,550,062,991
3	2,661,340,011	581,273,622	6,209,793,359	1,356,305,117
4	3,548,453,348	775,031,496	5,322,680,022	1,162,547,243
5	4,435,566,685	968,789,370	4,435,566,685	968,789,370
6	5,322,680,022	1,162,547,243	3,548,453,348	775,031,496
7	6,209,793,359	1,356,305,117	2,661,340,011	581,273,622
8	7,096,906,696	1,550,062,991	1,774,226,674	387,515,748
9	7,984,020,033	1,743,820,865	887,113,337	193,757,874
10	8,871,133,370	1,937,578,739	0	0

5.2.1 Results of Early and Late Benefits

Table 9 sums up the early and late benefits achieved in both time periods for all policy options. Policy A-- and A-+ have the same benefits in period one, this is because both policies are abating the lower level and will therefore reap the same benefits. Naturally, the highest benefits are achieved from strategy A++. Notice there are no late benefits in period one since benefits do not materialise until period two. Late benefits are of course much lower than early benefits since they appear later, and once discounted to the start of period one, are worth less than benefits that may appear earlier.

Table 9. Discounted early benefits and late benefits of policy A++, A--, A-+ in EUR.

	Policy	Period one	Period 2	Total
Early Benefit	A++	51,294,081,398	94,441,931,013	145,736,012,411
	A--	11,377,685,124	21,214,951,830	32,592,636,954
	A-+	11,377,685,124	61,488,868,804	72,866,553,928
Late Benefit	A++	0	98,654,772,961	98,654,772,961
	A--	0	21,547,572,629	21,547,572,629
	A-+	0	48,173,376,251	48,173,376,251

5.3 Results of Quasi Option Value

Figure 7 is similar to Figure 2 but we have included the results from Table 5, 6, 8, and 9. We are now in a position to calculate the quasi option value using Equation 6a from section 3.2. Using this equation, we find a quasi option value of 8,622,474,844 EUR. This means that value of information concerning whether benefits are received early or late from abatement is worth over 8.6 billion EUR to all governments. This is the value of waiting until period two to receive more information, before implementing irreversible abatement policy.

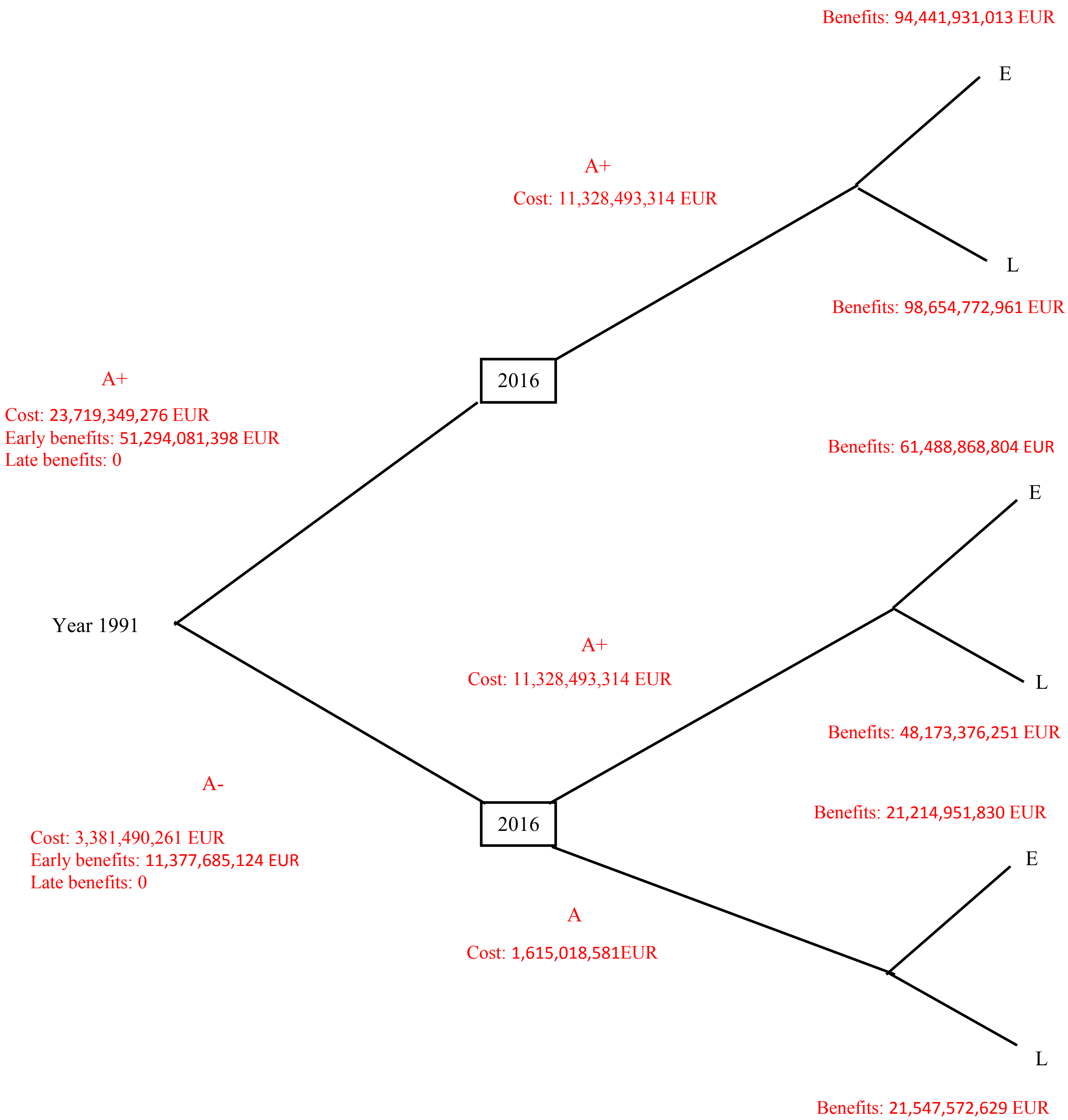

Figure 7. Decision tree showing all combinations of policy options available and corresponding discounted results in the two states of the world that could materialise.
A+, high abatement; A-, low abatement; E, early benefit; L, late benefit.

5.4 Sensitivity Analysis

We will now conduct some sensitivity analysis to see how our answers may change. Two main things could affect our results; the first is the discount rate we select, and the second being when early benefits are expected to materialise. We will run our formulations again with an interest rate of zero. Naturally, by using a discount rate of zero, the annual aggregated costs and benefits are the same in both periods (depending on which strategy is implemented). The costs of all policy options (A++, A--, A-+) are higher as shown in Table A1 and A2 in Appendix 3. Benefits are also higher since we are not valuing the future less than the present, this can be seen in Table A3 of Appendix 3. We find the quasi option value becomes 66.6 billion EUR. The quasi option value is higher using a discount rate of zero, making the value of information higher, this is understandable since the future benefits are not discounted. This reveals that the lower the rate we apply in discounting, the higher the value of information.

We also consider early benefits materialising in year 0, while the timing of late benefits does not change. Table A4 in Appendix 3 shows the expected early benefits. The quasi option now becomes 10 billion EUR. Intuitively; it is more valuable to have knowledge about the state of the world when early benefits are expected to occur earlier, rather than later. This is understandable since the benefits from abatement will be higher if benefits occur earlier (due to discounting).

6. Discussion and Conclusion

Our thesis was built on the premise of irreversible abatement policy, where we formulated two policy options; high abatement of nitrogen was assumed irreversible. We assumed two uncertain states of the world; one in which benefits were received early, and one where they were delayed. We created two time periods (now and the future), where the decision to undertake high or low abatement was made at the start of period one. However, information regarding the time lag of benefits was only visible at the end of period one. Using a cost function derived by Elofsson (2006), we determined the annual costs associated with both policy options. Benefits were calculated by integrating the demand curve for nitrogen reduction, to obtain the consumer surplus. We then used the quasi option value method to calculate the value of information.

We estimate the quasi option value of early information to be worth over 8.6 billion EUR, to all boarding countries of the Baltic Sea. This is the value attained from delaying irreversible decision making until more information is available, and hence the value of knowing which uncertain state of the world we are in.

6.1 Uncertainties Regarding Abatement

The quasi option value model has not been previously used to address uncertainty in the Baltic Sea, despite its successful application to numerous other environmental problems. Elofsson (2003) and Gren (2008c) study the uncertain, and stochastic relationship of abatement policy on nutrient loads. Similarly to our work, they motivate their research by highlighting the unclear outcomes of abatement policy. They both find the covariance of nutrient loads in a region (or country Gren (2008c)) largely affect the abatement policy that should be employed. Not accounting for covariance can often lead to underestimating costs, and diverging away from the cost effective abatement level. Our study builds on this research by determining how uncertain time lags affect abatement, focusing on the associated benefits from two uncertain states of the world. By valuing the information, we can determine if it is profitable to wait before implementing expensive abatement policies.

The above studies focus on how the uncertainties following abatement policy impact the level of abatement to be taken. Elofsson (2003) solves a cost minimisation problem with respect to different pollutant load reduction measures, to determine the cost effective abatement level. Gren (2008) uses stochastic programming to minimise costs, resulting in the optimal allocation of mitigation and adaptation measures. Our approach differs from previous studies as our method focuses on what the value of information would be regarding uncertainties on time lag. Unlike Elofsson (2003) and Gren (2008b), we do not calculate the cost effective levels of abatement, instead we assume the cost effective level is in fact the high abatement policy as assigned by HELCOM. Our results quantify the value of waiting, we argue that if it is profitable to wait for more information, a high abatement strategy (cost effective) will not be employed in period one, in order to keep the option of investing open until more information is attained (end of period one).

The uncertainties of abatement policy are often regarded as one of the reasons countries have failed to comply with load reduction targets. It is uncertain how long nutrients will take to leave the Baltic Sea, leading to uncertain benefits from abatement. If this information were to be known, then the governing body HELCOM could set more informed load reduction targets. Table 3 displayed the load reductions of the BSAP and the actual reductions made. Some countries failed to make any reductions. The uncertainty of benefits combined with irreversibility of policy, could be one of the reasons why some countries may feel it is not profitable for them to engage in nutrient reductions. By addressing this uncertainty, it may motivate these countries to follow allocated load reductions. We find this information is worth over 8.6 billion EUR, encouraging further research.

6.2 Limitations of Our Study

Our method successfully valued perfect information related to the uncertain time lag of benefits. However, our findings may need to be interpreted with caution due to the assumptions we have made. Firstly, we assume abatement costs remain the same throughout the policy period (1991-2040). By making this assumption, we disregard some important aspects like international knowledge diffusion and increasing technological change, which we acknowledged earlier. Knowledge diffusion could mean cost effective abatement choices are impacted by the potential for the abatement to add to the stock of experience, both domestically as well as abroad (Elofsson 2014). Whereas, it has been long established that technological innovation can lead to positive spill overs, and reduce the cost of abatement policy (see e.g. Löschel 2002, and Lindqvist and Gren 2013). Since we do not consider costs falling over time, we may have overestimated the costs following abatement.

In relation to this, since we assumed that costs are the same in every period, there are no potential benefits to reap from enforcing a high abatement strategy in period one. Therefore, our thesis considers the scenario that having high abatement in period two entails the same cost, despite the previous policy taken. This is unlikely and could overestimates our cost calculations. It is more likely there are some potential gains from using a high abatement strategy in period one e.g. in terms of learning by doing.

We have also assumed that benefits are the same every year (depending on which policy has been implemented). However, previous studies have revealed that nitrogen abatement contributes to the reduction of phosphorus pollution (Howarth 2005). This could mean we have underestimated the benefits of nitrogen reductions in our calculations, since we do not consider the subsequent phosphorus pollution reductions that could occur.

Algae production requires both nitrogen and phosphorus, however, a single nutrient is usually limiting growth, because both nutrients are needed in fixed proportions (Elofsson 2006). If a basin is phosphorus limited, then reducing nitrogen would have no effect, it would in fact be cost effective to only reduce phosphorus in this case. Our model abstracts away from considering the Baltic Sea as seven separate basins with different characteristics, instead we assume nitrogen reductions will benefit all basins equally. We combine benefits of all countries, and do not differentiate between basins or countries. This could potentially overestimate the benefits from abatement.

Our thesis is limited to considering only nitrogen abatement, although phosphorus is also harmful to the sea. We only take account of this nutrient due to the literature available. Hökby and Söderqvist (2003) finds the price elasticity of nitrogen reduction. This allowed us to integrate the demand function for nitrogen reduction and use a method by Gren et al (2009) to find the benefits from abatement. However, previous studies have not considered the elasticity of phosphorus reduction, so the same method could not be applied. Recall from section 2 that data on the benefits received from nutrient reductions can also be found using consumer valuation studies. We could not use this method since we wanted to distinguish the benefits attained from high and low abatement, hence we required a benefit function. Since we could not calculate a benefit function for phosphorus, we could not consider this nutrient.

One final point to consider is that our answer is very sensitive to the allocation of early and late benefits. Due to the time constraint of this thesis, we could only consider one possible realisation of early and late benefits. However, if we had more time, it could be beneficial to look at more timings of early and late benefits, and formulate a confidence interval of what the value of information could lay between.

6.3 Ethical Implications of Our Research

The choice of discount rate was an ethical issue we briefly discussed in section 4.4. By selecting a positive discount rate, we are valuing the future less than the present, this is highly debated since the stream of benefits received in the future is considered to be worth less than the current period. We attempt to account for this in the sensitivity analysis, where we recalculate the quasi option value with a zero discount rate. We found that this increased the value of information substantially.

Another ethical implication of our research findings relates to the distribution of benefits. The benefits are aggregated over all nine countries surrounding the Baltic Sea, with no consideration of how these benefits are actually divided amongst the countries. Our research question was considered on an international level. However, it is unlikely benefits will be distributed equally, since the willingness to pay for abatement are not equal across countries. Hyytiäinen et al (2013) combines a catchment, marine and economic model to weigh the costs and benefits of nutrient abatement. They find that the improved water quality benefited Sweden and Finland most, while Latvia and Lithuania benefited the least. This raises the ethical issue of how benefits are distributed, and who gains the most, we do not consider the political problems that could ascend with cooperation. To address this issue we could have found separate quasi option values for each country, allowing us to compare the value of information for each.

Furthermore, it can be argued that finding a high quasi option value suggests we can delay investing in abatement policy, until we achieve more information. This is of course an ethical implication since we know we must abate now. Nevertheless, this thesis is simply with the aim to quantify uncertainty, giving a possible value that information can be worth to justify if research is beneficial, and to explain a possible reason why countries may not be committing to load reductions. We argue that by putting a number on the uncertainty, it could motivate action.

6.4 Policy Relevance

One final factor to consider is the policy relevance. We believe our results can be used to guide policy making, despite the assumptions we have made. Our study has revealed it is valuable to conduct research into the timing of benefits, associated with abatement in the Baltic Sea. This area could benefit from increased research, aimed at eliminating this uncertainty. Thus making expected benefits more transparent, and therefore possibly motivating the affected countries to reduce emissions. There is a danger that countries may be discouraged to engage in abatement, if research finds that benefits are expected to be received with a substantial time lag. Nevertheless, more research should be conducted to find the value of other uncertainties in the Baltic Sea. These values could then be compared to what we have found, thus determining where it is most profitable to fund research.

6.5 Concluding Remarks

In conclusion, we have demonstrated the significance of using the quasi option value model to quantify the uncertainty of time lag. To the best of our knowledge, no previous work has been done to value the uncertainty of time lag, nor has this model been used to address uncertainties in the Baltic Sea. We have successfully applied this model to our research question, and calculated a value that could potentially inform policy.

Appendix 1

Our cost function was $\ln C_{ri}\ (e_{ri}) = \ \beta_1 + \beta_2 \ln(e_{ri}^0 - e_{ri})$, by setting $Q_{ri} = e_{ri}^0 - e_{ri}$ we get Equation A1

$\ln C_{ri}\ (e_{ri}) = \ \beta_1 + \beta_2 \ln(Q_{ri})$ **[A1]**

Applying exponential we get $e^{lnC_{ri}(e_{ri})} = e^{\beta_1 + \beta_2 lnQ_{ri}}$ **[A2]**

Hence $C_{ri}(e_{ir}) = e^{\beta_1 + lnQ_{ri}^{\beta_2}}$ **[A3]**

This can be written as $C_{ri}(e_{ir}) = \ e^{\beta_1} Q_{ri}^{\beta_2}$ **[A4]**

Leading to $C_{ri}(e_{ir}) = \ KQ_{ri}^{\beta_2}$ **[A5]**

Where $K = e^{\beta_1}$ **[A6]**

Equation A5 is differentiated to obtain the marginal cost curve, this is written as Equation 7 in the main text

$\frac{\partial C_{ri}(e_{ri})}{\partial Q_{ri}} = \ \beta_2 K Q_{ri}^{\beta_2 - 1}$ **[7]**

Appendix 2

The demand function is Equation A8 (taken from Gren et al (2009))

$X_{ijh} = a_{ijh} - b_{ijh} P_{ijh}$ **[A8]**

$\boldsymbol{a_{ijh}}$ is a constant, which represents the intercept of the demand curve while $\boldsymbol{b_{ijh}}$ is the coefficient, which represents the slope of the demand curve. Finally $\boldsymbol{X_{ijh}}$ and $\boldsymbol{P_{ijh}}$ are the consumer quantity, and price demanded respectively. Equation A9 and A10 define $\boldsymbol{a_{ijh}}$ and $\boldsymbol{b_{ijh}}$.

$a_{ijh} = (1 + \varepsilon_{ijh}) * X_{ijh}$ **[A9]**

and

$$b_{ijh} = \frac{X_{ijh}\varepsilon_{ijh}}{p_{ijh}} \qquad \textbf{[A10]}$$

Where ε_{ijh} is equal to the income elasticity, which we know is equal to -1.86 from Hökby and Söderqvist (2003).

The inverse demand function simply becomes

$$P_{ijh} = \frac{a_{ijh}}{b_{ijh}} - \frac{X_{ijh}}{b_{ijh}} \qquad \textbf{[A11]}$$

Equation A11 is what we need to integrate with respect to quantity, to get the benefits of abating the quantity $\boldsymbol{X_{ijh}}$.

$$\int_0^{X_{ijh}} \frac{a_{ijh}}{b_{ijh}} - \frac{X_{ijh}}{b_{ijh}}\, \partial X \qquad \textbf{[A12]}$$

The integration of this is written as Equation 8 in the main text, which is the benefit function

$$\frac{a_{ijh}}{b_{ijh}} X_{ijh} - \frac{X_{ijh}^2}{2b_{ijh}} + C \qquad \textbf{[8]}$$

Appendix 2.1

We assume that for early benefits between year 10 and 20, and for late benefits between year 25 and 35, benefits follow a linear change. We use the equation of a line; Y= mX + b, where m is the slope and b is the intercept on the Y-axis, to determine the level of benefits in each of these years. We calculate the slope using ΔY/ΔX, this is simply the change in the Y-axis, divided by the change in the X-axis. We will use the point when stable benefits are reached (year 20 for early and year 35 for late) to calculate this. The change in the Y-axis is simply the stable level of benefits achieved, while the change in the X-axis is 10 years. After we have the slope, we can find the intercept by rearranging the equation to b= Y- mX. We will then have the equation of the line, and use this to derive the corresponding benefits between when benefits start, and when stable benefits are achieved by simply inserting different years into the equation (Y= mX +b).

Appendix 3

Table A1. Aggregated country costs of strategy A++ in EUR (1991-2015 and 2016-2040) with discount rate 0.

Country	Discounted Aggregate Costs 1991-2015	Discounted Aggregate Costs 2016-2040
Denmark	9,707,216,106	9,707,216,106
Estonia	7,640,402	7,640,402
Finland	6,013,361	6,013,361
Germany	1,359,221,403	1,359,221,403
Latvia	25,837,534	25,837,534
Lithuania	1,593,964,015	1,593,964,015
Poland	16,987,778,885	16,987,778,885
Russia	619,321,078	619,321,078
Sweden	2,754,942,443	2,754,942,443
Total Cost	**33,061,935,228**	**33,061,935,228**

Table A2. Aggregated country costs of strategy A--/A-+ in EUR (1991-2015 and 2016-2040) with discount rate 0.

Country	Discounted Aggregate Costs 1991-2015 (A-)	Discounted Aggregate Costs 2016-2040 (A-)	Discounted Aggregate Costs 2016-2040 (A+)
Denmark	4,206,606,588	4,206,606,588	9,707,216,106
Estonia	0	0	7,640,402
Finland	0	0	6,013,361
Germany	12,056,528	12,056,528	1,359,221,403
Latvia	0	0	25,837,534
Lithuania	292,051,134	292,051,134	1,593,964,015
Poland	0	0	16,987,778,885
Russia	0	0	619,321,078
Sweden	202,678,629	202,678,629	2,754,942,443
Total Cost	**4,713,392,890**	**4,713,392,890**	**33,061,935,228**

Table A3. Early and late benefits with zero discount rate, in EUR.

	Policy	Period one	Period 2	Total
Early Benefit	**A++**	93,146,900,387	350,409,768,123	443,556,668,510
	A--	20,344,576,760	76,534,360,192	96,878,936,953
	A-+	20,344,576,760	258,592,330,297	278,936,907,057
Late Benefit	**A++**	0	443,556,668,510	443,556,668,510
	A--	0	96,878,936,952	96,878,936,952
	A-+	0	278,936,907,057	278,936,907,057

Table A4. Early benefits assuming year 0 start, in EUR.

Policy	Period one	Period 2	Total
A++	122,136,428,430	84,424,757,851	206,561,186,281
A--	26,676,292,319	18,439,539,688	45,115,832,008
A-+	26,676,292,319	74,188,059,671	100,864,351,991

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