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Analysis

Value of adaptation in water protection — Economic impacts of uncertain climate change in the Baltic Sea

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ABSTRACT

Uncertain drivers of pollution hinder long-term planning of management of aquatic ecosystems. This paper presents a framework for adjusting optimal water protection in the long term when the true trend in nutrient loading is unknown to the decision maker but can be gradually learned by monitoring stochastic nutrient loads. The economic impacts of an unknown trend consist of (i) the damage caused by the worsened state of the sea, (ii) the cost of nutrient abatement to counter the development and (iii) the adjustment costs caused by uncertainty and imperfect learning. An integrated assessment model is designed and calibrated for quantitative results pertaining to the uncertain impacts of climate change on nutrient input to the Baltic Sea. Under certainty, the net economic impacts from the currently anticipated climate change are 15.0 billion euros, of which 23% comes from welfare losses caused by aggravated eutrophication and 77% from increased abatement costs. The expected adjustment costs due to uncertain future development range from 90 million euros in the case of adaptive management based on Bayesian learning to as much as 7960 million euros in the case of an extreme variant of inadaptive management based on constant abatement levels. If adaptive management is adopted, there is no need to account for future climate change when planning the current abatement targets.

1. Introduction

Eutrophication, defined as excessive accumulation of nutrients in water bodies, is a major problem for inland, coastal, and semi-enclosed marine areas worldwide. Anthropogenic distortions of nitrogen and phosphorus cycles have severely damaged aquatic ecosystems, and these interferences are recognized as being among the most serious environmental threats (Rockström et al., 2009). The eutrophication problem is far from being solved (Albiac, 2009) and is likely to worsen in the future due to global climate change and anticipated socio-economic developments, such as rapid agricultural expansion (Tilman et al., 2001). The baseline development of polluting nutrient loads is often difficult to project with confidence due to uncertain impacts and inadequate information on the future evolution of the relevant social and natural processes.

Uncertainty regarding the trend in nutrient emissions creates a major challenge for the design of water protection policies. One way to address this uncertainty is adaptive management, in which the effort invested in water protection is adjusted in an iterative manner based on observed changes in pollution loads or the state of the focal aquatic ecosystems (Walters, 1997). Several considerations complicate implementation of adaptive management, however. First, there may be a significant administrative burden in the form of monitoring pollution levels and inputs and revising the restoration targets periodically. Second, the high level of annual variability in waterborne nutrient emissions hampers adaptive management by making it difficult to observe trends in nutrient loading. Peaks in nutrient emissions can result from exceptional weather conditions but may equally well indicate an increasing baseline trend. Nevertheless, the true trend in nutrient loading – and consequently the true marginal benefits of abatement – can be learned by monitoring a sequence of stochastic loads serving as imperfect signals of the true baseline. In this study we present an integrated assessment model for decision making in water protection under uncertainty and learning. The model is then applied to assess the benefits of adaptive management in protecting the Baltic Sea, which is a shallow and brackish marine area in northern Europe. We show that an increasing baseline development of nutrient loads causes damage through three mechanisms: additional damage from aggravated eutrophication, increased abatement costs to counter the effects of increasing loads, and the adjustment costs from uncertainty about and imperfect learning of the true underlying trend. The size of these adjustment costs depends on the management strategy and they can be significantly reduced by adopting adaptive management.

Uncertainty and learning from environmental stressors have been studied by including Bayesian learning in a stochastic dynamic

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programming problem that describes the social planner's optimal intertemporal decision making. In their seminal study, Kelly and Kolstad (1999) analyze learning about the relationship between greenhouse gas levels and the global mean temperature. Modeling the learning process has since been enriched to study the effect of learning on precautionary behavior (Gollier et al., 2000), to account for autocorrelation in temperature shocks (Leach, 2007) and to investigate the value of reducing uncertainty (Newbold and Marten, 2014).[1] Another branch of the literature analyzes the economic consequences of climate change based on the reaction of economic agents, arguing that optimal adaptation and learning can significantly reduce damage due to climate change. This approach has been applied to agriculture (Schneider et al., 2000; Kelly et al., 2005) and forestry (Guo and Costello, 2013). However, to our knowledge there are no studies that have analyzed the optimal management of eutrophication with reference to uncertainty and learning, even though uncertainty is an inherent feature of water management and much has been written about adaptive management in water protection on a general level (e.g. Walters and Hilborn, 1978; Walters, 1997; Linkov et al., 2006). Our study contributes to the literature in being the first attempt to analyze how eutrophic water bodies can be efficiently managed under uncertain baseline development by using Bayesian learning and adaptive management. Furthermore, we introduce and apply an empirical model for quantitative estimates of welfare gains from adaptive management.

Eutrophication is a phenomenon that is characterized by non-convex system dynamics and the interaction of several nutrients that are imperfect substitutes in phytoplankton production. Several studies have used what are known as shallow-lake models to analyze non-linear dynamics in water bodies where phosphorus limits phytoplankton growth (e.g. Mäler et al., 2004; Hein, 2006; Chen et al., 2012). Models focusing solely on phosphorus are not generally applicable, as a strong consensus prevails among ecologists that nitrogen is the primary cause of eutrophication in many water areas, particularly ones suffering from excessive cyanobacterial blooms (Howarth and Marino, 2006).[2] The interplay of the two nutrients, nitrogen and phosphorus, needs to be carefully considered in nitrogen-limited water areas; otherwise models lead to suboptimal, or even perverse, policy recommendations. For instance, it is well known that where nitrogen limits phytoplankton growth, unbalanced nitrogen reductions will lead to excessive cyanobacterial blooms[3]; yet, this is a result that cannot be reproduced by earlier models that either focus exclusively on nitrogen or nitrogen-equivalents (Hart and Brady, 2002; Hart, 2003; Laukkanen and Huhtala, 2008) or neglect the role of cyanobacteria (Kuosmanen and Laukkanen, 2011; Ahlvik and Pavlova, 2013). Our study contributes to the literature on the economics of shallow lakes by introducing a two-stock variant of the shallow lake model that incorporates both the non-linear dynamics and interaction of several nutrients. The model allows us to analyze both phosphorus- and nitrogen-limited water bodies and makes it possible to address questions such as how to strike an efficient balance between nitrogen and phosphorus abatement.

We apply the model to determine the optimal nutrient abatement in the Baltic Sea under uncertain impacts of climate change. Increasing temperatures will accelerate the decomposition of organic matter in terrestrial and aquatic ecosystems and, together with increased precipitation, are likely to increase nutrient loading in the Baltic Sea region (Meier et al., 2012). The large uncertainties regarding climate impacts are reflected in quantitative estimates of climate change impacts: It is estimated that the total water flow will change by −2–17% (Graham, 2004; Meier, 2006) and nutrient loading by −3–20% (Meier et al., 2011, 2012). The most recent step taken to mitigate eutrophication is the conclusion of the Baltic Sea Action Plan (BSAP), in which the littoral countries have agreed on significant reductions in the nitrogen and phosphorus loads to the sea (HELCOM, 2007, 2013a). The Helsinki Commission (HELCOM) applies adaptive management in that the BSAP targets will be periodically revised as knowledge of the future development of the sea accumulates (HELCOM, 2013b, 2013c). On the other hand, the BSAP is not precautionary, for it does not impose additional efforts immediately to offset uncertain and undesirable future developments.[4] According to the background document of the agreement:

> At present, scientific knowledge and tools are not in place to make a proper assessment of [maximum allowable inputs] under the constraints of climate change … However, at present, the best foreseeable way to handle climate change issues is to initiate a cyclical revision of [maximum allowable inputs] (HELCOM, 2013c, p.17).

This study contributes to the literature on optimal nutrient abatement in the Baltic Sea (Gren et al., 1997; Hart and Brady, 2002; Laukkanen and Huhtala, 2008; Lindkvist et al., 2012; Hyytiäinen et al., 2014) by introducing uncertainty and anticipated learning in the management problem. The paper specifically studies the question whether the approach chosen by HELCOM, based as it is on adaptive but not precautionary management, is justified, and investigates how such “cyclical revision” can be put into practice as the true impact of climate change becomes known.

2. Theoretical Model

2.1. Integrated Assessment Model for Water Protection

In this section we introduce a model to evaluate optimal mitigation of eutrophication in an aquatic ecosystem, henceforth broadly referred to as “the sea”. Fig. 1 illustrates a stylized representation of the model, which incorporates the core ecological processes characterizing eutrophication: (1) the interplay of the two most important nutrients, nitrogen and phosphorus, which are imperfect substitutes in phytoplankton production; (2) the non-linear nutrient dynamics caused by negative and positive feedback mechanisms; and (3) the annual variability in waterborne nutrient inputs.

The concentrations of nitrogen and phosphorus, the two main nutrients limiting the growth of phytoplankton in many aquatic ecosystems, are the state variables in the model. When occurring in excessive amounts, phytoplankton causes damage in the form of reduced recreational opportunities, negative health effects, an increased area of anoxic sea floor and altered functioning and composition of the aquatic food web. Phytoplankton is divided into cyanobacteria (blue-green algae, B_t) and algae (A_t), of which the latter are not able to fix molecular nitrogen.[5] We consider a social planner who chooses levels of nitrogen Δn_t and phosphorus Δp_t abatement ($\Delta n_t \geq 0$, $\Delta p_t \geq 0$) to minimize the sum of environmental damage from algae and cyanobacteria, $D(A_t, B_t)$, and the cost of nutrient abatement, $C(\Delta n_t, \Delta p_t)$.[6] Possible transaction costs are not included in the objective function, but they will be discussed later in Section 5.[7] For simplicity, we assume that the social planner can choose nitrogen and phosphorus abatement levels flexibly

[1] In addition, there are a number of studies that analyze the uncertainties related to the causes of climate change (van Wijnbergen and Willems, 2015), climate sensitivity (Keller et al., 2004; Jensen and Traeger, 2013), the location of a climate tipping point (Lemoine and Traeger, 2014) and damage caused by increased temperatures (Gerlagh and Liski 2014).

[2] Nitrogen is a limiting nutrient in at least some parts of Lake Erie, the Gulf of Mexico, the Chesapeake Bay, the Baltic Sea, the Black Sea and Lake Taihu, to name a few examples.

[3] See Schindler et al. (2008) for a large-scale natural experiment confirming this result.

[4] This definition of “precautionary behavior” is similar to that applied in e.g. Gollier et al. (2000).

[5] Other potentially limiting nutrients, such as silicon for diatoms, are excluded from this analysis. If silicon limits growth in some areas, diatoms are replaced by other nitrogen-limited species and the total biomass of algae as defined in this study remains unchanged.

[6] Incentives of single countries to deviate from the agreed terms and all other game-theoretical considerations (as in Ahlvik and Pavlova, 2013) are outside the scope of this study.

[7] In Section 5.2 we use welfare gains from more sophisticated management strategies as upper bounds for lump-sum transaction costs at which those strategies become worthwhile.