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Abstract

This paper analyzes the implications of international knowledge diffusion for the costs of Baltic-wide policy to reduce nutrient emissions to the Baltic Sea. In particular, the impact on the distribution of abatement and costs over time and space is investigated, and the relative importance of knowledge spillovers between countries and nutrient spillovers between marine basins is examined. Using a spatial and dynamic cost-effectiveness model over the Baltic Sea drainage basin, it is shown that theoretically, the presence of knowledge spillovers could imply that abatement can be cost-effective even if the cost is comparatively high and the impact on water quality is zero. The empirical simulations show that a more likely outcome is that higher knowledge dispersal leads to a further concentration of abatement to countries with large, low-cost abatement opportunities.

Keywords: knowledge spillovers, learning-by-doing, Baltic Sea, nitrogen, phosphorus, cost-effectiveness

Introduction

Eutrophication of the Baltic Sea has been recognized as a major problem since the 1960s (Boesch et al., 2006). Excessive nutrient loads are considered a major explanation to the current situation. Over the last decade, there has been a downward trend in nutrient inputs to the sea, but the internationally agreed targets for nutrient reductions have not been reached and still seem far away (HELCOM, 2013). Possible reasons for limited action in the countries surrounding the sea are the large costs of significant load reductions and the political difficulties to distribute these costs among different countries and stakeholders (Gren, Elofsson and Jannke, 1997; Gren, 2001; Markovska and Zylicz, 1999; Wulff et al., 2014; Ahlvik and Pavlova, 2013). Moreover, it is well known that it takes considerable time for the sea to respond to changes in nutrient inputs, for nitrogen the adjustment to a new steady state could occur over a few decades, but for phosphorus this could take much longer time, more than a half century (Savchuk and Wulff, 2007). The high cost of achieving agreed nutrient reductions in combination with the long time scale to be considered before the ecosystem is restored raises the question of whether abatement costs will fall over time. If they do, this would facilitate achieving the Baltic Sea water quality targets, while also having implications for the allocation of costs and abatement over time and across countries.

Costs for pollution abatement can be expected to fall over time due to successively increased knowledge, achieved either through investment in research and development, R&D, or through learning from experience (Newell, 2009; Löschel, 2002; Ek and Söderholm, 2010). Learning by experience, also called learning-by-doing, can reduce abatement costs over time as the cost of using a particular technology may depend both on the extent to which a particular user has, himself, applied the technology before, and on the number of other users which have already adopted the technology. The learning-by-doing concept is since long established in the literature (Wright, 1936; Arrow, 1962), where the impact of learning on costs is typically measured empirically as learning or experience curves, which identify the relationship between abatement costs and the cumulative use of the technology (McDonald and Schrattenholzer, 2001). Most empirical studies on endogenous learning in partial models have been applied to the energy sector (see Berglund and Söderholm, 2006 for a review), and corresponding analyses of the costs for environmental technologies in the agricultural and wastewater sectors, which are the major sources of nutrient emission to the Baltic Sea, seems not to be available. Studies applied to agri-environmental issues instead typically investigate determinants of the adoption of agri-environmental technologies while focusing on farmer and farm characteristics (Morris and Potter, 1995; Vanslembrouck et al., 2002; Hynes and Garvey, 2009; Fuglie and Kascak, 2001; Defrancesco et al., 2008; Buckley et al., 2012). Some also take into account from who the farmer gets technical advice, and whether they have previous experience of the measure (Defrancesco et al., 2008; Morris and Potter, 1995; Vanslembrouck et al., 2002; Buckley et al., 2012), but do not model adoption as a consequence of the cumulative experience. For wastewater, there is very limited research on technology adoption. An exception to the rule is Kemp (1998), which investigates the impact of economic incentives on wastewater technology adoption, but does not take into account the role of knowledge or experience.

Whereas the above studies focus on the role of learning or technology adoption within a specific country or region, there is also a literature which investigates cross-country diffusion of knowledge. This literature concentrates on diffusion of knowledge achieved through R&D. Examples include Popp (2006), which examines the link between regulatory stringency and innovation across countries for coal fired plants in USA, Japan and Germany. He shows that innovative activity mainly responds to regulation stringency within the home country, and that adaptive research and development is typically necessary for a new technology to be adopted in another country. Openness to trade is shown to be important for the cross-country diffusion of new technologies (Lovely and Popp, 2008). Countries' could learn more rapidly about new technologies and their use if they import relatively more from countries with larger technological knowledge, if technology is embodied in the imported products (Keller, 2004; Coe and Helpman, 1995). Hypothetically, larger exports could imply that more knowledge is acquired through interaction with foreign customers, which might require different product standards, but there is stronger empirical evidence on the role of imports compared to the role of exports for technology diffusion (Keller, 2004; Bernard and Jensen, 1999). Other factors of potential importance for technology diffusion are the geographical distance between countries (Keller, 2002; Bottazi and Peri, 2003) and human capital in the receiving country (Eaton and Kortum, 1996; Xu, 2000). Van Meijl and van Tongeren (2004) draw on the experience of the above literature to model the role of knowledge spillovers for GMO uptake in different world regions, including simultaneously several of the above mentioned drivers of knowledge diffusion in a static general equilibrium model, with an aim to compare modeled and actual GMO.

The purpose of this paper is to investigate the implications of international knowledge diffusion for the costs of Baltic-wide policy to reduce nutrient emissions to the Baltic Sea. In particular, the aim is to identify the implications of international knowledge diffusion for the distribution of abatement and costs over time and space. Moreover, we note that there are two different diffusion processes of relevance for the management of Baltic Sea eutrophication, that of knowledge dispersal between countries and that of nutrient dispersal between different marine basins. We contrast and compare these two processes with regard to their impact on the distribution of abatement and costs over time and across space.

The role of information and learning has earlier been investigated in the Baltic Sea context by Lindqvist and Gren (2013), which model the implications of domestic learning but abstract from knowledge dispersal between countries, and by Elofsson (2007), where a two-agent sequential game is used to investigate incentives for acting as a fore-runner in order to reduce abatement cost uncertainty for followers. Compared to Lindqvist and Gren (2013), this study contributes through the inclusion of cross-country diffusion of knowledge. When modelling of cross-country dispersal of knowledge, the present study draws on the above mentioned literature on determinants of cross-country knowledge spillovers, in a similar manner as in van Meijl and van Tongeren (2004), but this study differs from van Meijl and van Tongeren (2004) through the focus on the implications for a dynamically cost-effective pollutant abatement scheme.

The paper is organized as follows; in the following section, the analytical model is presented. This is followed by a presentation of first data, and then results. The paper ends with discussion and conclusions.

Model

Consider an aquifer that is negatively affected by nitrogen emissions from human activities in the surrounding watershed. The watershed is divided into $i=1,\ldots,n$ regions. There are two different nutrients r emitted to the aquatic environment, nitrogen and phosphorus, implying that we have

r=$N,P,$ where N denotes nitrogen and P phosphorus. The aquifer itself consists of several, coupled marine basins b, with b=1,...,m different basins.

The emissions of a nutrient from land-based sources in region i to a marine basin b at a given time t are defined as Q_{ibrt} . The total nutrient load to a given marine basin consists of discharges from its own catchment, $\sum_i Q_{ibrt}$, and nutrient transports from other sea basins. Following Gren, Savchuk and Jansson (2013), it is assumed that nutrient transports among basins can be described by a coefficient matrix, where each coefficient α_{blr} in the matrix shows the transports of nutrient loads from basin l to basin b as a share of total emissions to basin l. Total nutrient load to a sea basin b, L_{bt}, is then written as:

$$L_{bt} = \sum_l \alpha_{blr} \sum_i Q_{ilrt} \qquad (1)$$

where α_{bir} is the fraction of emissions to basin l that enter basin b. The transport term α_{bir} is assumed to be constant, and hence independent of the emissions, loads and nutrient concentrations in the sea.

The time required for adjustments to a change in emissions differs between sea basins and nutrients. Phosphorus is stored in bottom sediments, but can be released into the water body if phosphorus loadings are reduced, hence slowing down the adjustment of phosphorus concentration in the water body. Some of the nitrogen in the sea is denitrified into harmless nitrogen gas and thus disappears from the water body, while nitrogen can also be taken up by the sea from the atmosphere through nitrogen-fixing cyanobacteria. The magnitude of these processes varies between sea basins and affects response times. Further, nitrogen and phosphorus pools can be interdependent, and their response to emissions changes is potentially non-linear

(Savchuk and Wulff, 2009), implying difficulties to identify optimal solutions. For tractability, we follow Gren, Savchuk and Jansson (2013) by assuming a simple linear relationship between the stock of nutrient in period t+1 in basin b, $S_{br,t+1}$, and the nutrient stock and load in the foregoing time period t according to:

$$S_{br,t+1} = (1-\tau_{br})S_{brt} + L_{brt} \quad \text{and} \quad S_{br0} = \overline{S}_{br0}, \tag{2}$$

where $\tau_{br} \in (0,1)$ is the decay rate of the nutrient stock. Assuming that policy makers have decided on an environmental target in terms of maximum tolerable nutrient pools, S^*_{bT}, where this target should be achieved in year T, the environmental target for each nutrient and marine basin can be defined as:

$$S_{brt} \le S^*_{brT} \tag{3}$$

It is assumed that national policy makers want to reach these targets at minimum cost. There are assumed to be several littoral countries f, with f=1,…,h, in the watershed, and each region i belongs to a particular country f. Furthermore, it is assumed that there are cost functions for nutrient reductions, which are determined by the reductions made in the same time period and by the knowledge stocks of the two nutrients K_{frt}. The cost of abatement of nutrient r in country f can then be written as $c_{frt}(Q_{irt}, K_{frt}) \forall i \in f$. The cost functions are assumed to be increasing and convex in Q_{irt}, and decreasing and convex in K_{frt}, and the instantaneous abatement cost is assumed to be additively separable in nitrogen and phosphorus knowledge stocks (Bramoullé and Olson, 2005). We thus exclude the possibility that knowledge about nitrogen abatement technologies would lower the abatement cost for phosphorus. This is a simplification, as some abatement measures in the agricultural sector, such as wetlands, and measures to improve manure management, affect both nitrogen and phosphorus emissions to the sea (Gren, Elofsson and Jannke, 1997; Elofsson, 2010). The simplification is motivated by the aim to investigate the role of knowledge diffusion between countries. Also, there are difficulties to identify the possible relationship between knowledge stocks for the two nutrients, given that such interdependent knowledge stocks have not earlier been modeled in the empirical literature.

Following Bramoullé and Olsson (2005) we parameterize the cost function as

$$c_{frt}\left(Q_{irt}, K_{frt}\right) = c_{frt}\left(Q_{irt}\right) K_{frt}^{-\mu}, \forall i \in f . \tag{4}$$

This formulation of the cost function exhibits the standard learning curve properties where a doubling of the knowledge stock leads to a reduction of costs by a fixed factor ($1-2^{-\mu}$), also called the learning rate. The knowledge stock in (4) is assumed to differ between countries and nutrients.

We assume that the cumulative level of abatement of nutrients determines the knowledge stock and following, e.g., Keller (2004), we also assume that there is a diffusion of knowledge from country *g* to country *f*, expressed by a parameter β_{fg}. The development of the knowledge stock is then defined by:

$$K_{fr,t+1} = K_{frt} + \sum_{g \neq f} \beta_{fg} \sum_{i \in g} \left(\bar{Q}_{ir} - Q_{irt} \right) , \tag{5}$$

where $K_{fr0} = \bar{K}_{fr0}$ is the exogenously determined knowledge stock at time t=0, and $\bar{Q}_{ir}$ is the maximum reduction that can be achieved for a particular nutrient from a given country.

As shown in the literature, observed reductions in abatement costs could be the result of both learning from experience and efforts spent on R&D. Many studies include only one of these factors but attempts have been made to empirically disentangle the relative importance of those for certain energy technologies (Söderholm and Sundqvist, 2007; Söderholm and Klaassen, 2007; Klaassen et al., 2005; Nemet, 2006). The assumption made here about cost reductions being determined only by experience is thus a simplification, motivated by our focus on international knowledge spillovers and the lack of knowledge about the impact of R&D on the costs of nutrient abatement.

The decision problem of the environmental agent who wants to reduce nutrient loads to the aquifer can then be written as:

$$\underset{Q_{irt}}{\text{Max}} \sum_{f} \sum_{r} \sum_{t} -\rho^{t} c_{frt} \left(Q_{irt}, K_{frt} \right)$$

s.t.

$$\begin{aligned}
&K_{fr,t+1} = K_{frt} + \sum_{g \neq f} \beta_{fg} \sum_{i \in g} \left(\bar{Q}_{ir} - Q_{irt} \right) \\
&L_{brt} = \sum_{l} \alpha_{blr} \sum_{i} Q_{ilrrt} \\
&S_{br,t+1} = \left(1 - \tau_{br} \right) S_{brt} + L_{brt} \qquad (6)
\end{aligned}$$

and

$$\begin{aligned}
&S_{br0} = \bar{S}_{br0} \\
&S_{brt} \leq S^{*}_{brT} \\
&Q_{irt} \leq \bar{Q}_{ir}
\end{aligned}$$

where $\rho^t = \left(1/\left(1+\delta\right)\right)^t$ is the discount factor, in which δ is the discount rate. The optimal allocation of load reductions can be determined from the solution to the above cost minimization problem. Setting up the discrete time dynamic Lagrangian gives:

$$L = \sum_{1}^{T-1} \rho^t \left[\begin{array}{l} \sum_f -c_{frt}\left(Q_{irt}, K_{frt}\right) - \rho \sum_i \sum_r \mu_{ir,t+1} \left(K_{frt} + \sum_{g \neq f} \beta_{fg} \sum_{i \in g} \left(\bar{Q}_{ir} - Q_{irt} \right) - K_{fr,t+1} \right) - \\ \rho \sum_b \sum_r \lambda_{br,t+1} \left(\left(1-\tau_{br}\right) S_{brt} + \sum_l \alpha_{brl} \sum_i Q_{ilrt} - S_{br,t+1} \right) - \sum_r \eta_{irt} \left(Q_{irt} - \bar{Q}_{ir} \right) \end{array} \right] \\ -\rho^T \sum_b \sum_r \lambda_{brT} \left(S_{brT} - S^*_{brT} \right) \tag{7}$$

where $\lambda_{rt} \geq 0$ and $\mu_{irt} \geq 0$ are the co-state variables for the nutrient and knowledge stocks, respectively, and $\eta_{it} \geq 0$ is the Lagrange multiplier for the emission reduction capacity constraints. The objective function is concave, according to assumptions made about cost functions. The constraints are differentiable and quasi-convex, implying that the Lagrangian is concave in Q_{irt}. Assuming that there exists an interior point Q^*_{irt} that satisfies the conditions in (6), the following conditions are necessary and sufficient for a global solution to the problem stated in (6).

$$\begin{aligned} &\rho^{-t} \frac{\partial L}{\partial Q_{irt}} = -\frac{\partial c_{frt}}{\partial Q_{irt}} + \rho \sum_g \mu_{gr,t+1} \beta_{gf} - \rho \sum_b \lambda_{br,t+1} \sum_l \alpha_{blr} \leq 0, \\ &\rho^{-t} \frac{\partial L}{\partial Q_{irt}} Q_{irt} = 0, \; Q_{irt} \geq 0 \end{aligned} \tag{8}$$

$$\rho^{-t}\frac{\partial L}{\partial K_{frt}}=-\frac{\partial c_{frt}}{\partial K_{frt}}-\rho\mu_{ir,t+1}+\mu_{irt}=0 \tag{9}$$

$$\rho^{-t}\frac{\partial L}{\partial S_{brt}}=-\rho\lambda_{br,t+1}\left(1-\tau_{br}\right)+\lambda_{brt}=0 \tag{10}$$

$$\rho^{-t}\frac{\partial L}{\partial\rho\lambda_{br,t+1}}=\left(1-\tau_{br}\right)S_{brt}+\sum_{l}\alpha_{blr}\sum_{i}Q_{ilrt}-S_{br,t+1}=0 \tag{11}$$

$$\begin{aligned}&\rho^{-t}\frac{\partial L}{\partial\rho\lambda_{brT}}=\left(\left(1-\tau_{br}\right)S_{br,T-1}+\sum_{l}\alpha_{brl}\sum_{i}Q_{irl,T-1}-S_{brT}^{*}\right)\leq 0\\&\rho^{-t}\frac{\partial L}{\partial\rho\lambda_{brT}}\rho\lambda_{brT}=0,\ \rho\lambda_{brT}\geq 0\end{aligned} \tag{12}$$

$$\rho^{-t}\frac{\partial L}{\partial\rho\mu_{ir,t+1}}=K_{frt}+\sum_{g\neq f}\beta_{frg}\sum_{i\in g}\left(\bar{Q}_{ir}-Q_{irt}\right)-K_{fr,t+1}=0 \tag{13}$$

$$\rho^{-t}\frac{\partial L}{\partial\eta_{irt}}=Q_{irt}-\bar{Q}_{ir}\leq 0 \tag{14}$$

Equation (8) tells that the optimal emission reduction is determined such that the marginal cost of nutrient emission reductions in country *i* to basin *b* equals the discounted shadow value of the future impact on the knowledge stock in all countries, plus the discounted shadow value of the impact on the nutrient stock in all basins. Thus, if a region is located in a country with large knowledge spillovers on other countries, more abatement should be undertaken in that region. Similarly, if emission reductions in a region has a large impact on nutrient stocks in marine basins with stringent nutrient targets, more abatement should be undertaken in that region. Hence, it can be cost-effective to undertake nutrient abatement in regions with little impact on nutrient stocks in the sea, if the knowledge spillovers on other countries are large enough.

Equation (9) shows that the current value of the knowledge stock in country *i* at time *t*, which is determined by its marginal cost-reducing impact and its shadow value in the same time period, must equal the discounted shadow value of the knowledge stock in the following time period. Equation (10) tells that the current shadow cost of the stock of nutrient *r* in basin *b* must equal the economically and biologically discounted shadow cost of the same stock in the next time period. Equations (11) and (12) restate, respectively, the equation of motion for nutrient stocks, and the stock restriction in the final time period. Equation (13) and (14) restate, respectively, the equation of motion of the knowledge stock and the capacity constraint on load reductions.

Compared to a situation where there is only domestic learning but no diffusion of knowledge, i.e. $\beta_{fg} = 0, \forall g \neq f$, the allocation of abatement between regions and countries will change. First, more abatement will be undertaken in regions where the marginal cost of additional abatement is low, and where the diffusion of knowledge from that country to other countries is high. However, it is not sufficient that the diffusion terms, β_{fg}, for country *g* where the regions is located are high, but the countries *f*, which receive the knowledge should also be countries that would abate much even if there were no knowledge spillovers between countries. This is because knowledge spillovers affect the costs of all abatement made in country *f*. When knowledge spills over, the average abatement cost falls in country *f*, and the cost saving made due to the spillover will be larger the larger is total abatement in country *f*. Moreover, the cost saving which results from knowledge spillovers is the largest if the receiving country *f* has a flat marginal cost function, implying that the country will increase its abatement considerably when there is knowledge diffusion, thereby reducing the need for more costly abatement in other countries.

Data

Data on unregulated loads, $\bar{Q}_{ir}$ are measured as the biologically available fractions of nutrient loads, which affect eutrophication. Unregulated loads are here measured as contemporary loads 1997–2003, and data have been obtained from Gren, Savchuk and Jansson (2013). Data on initial nutrient stock in each marine basin, decay rates, target nutrient stocks, and transports among marine basins have been obtained from the same source, where estimates have been obtained from simulations made with an oceanographic model, SANBALTS, which is further described in Savchuk and Wulff (2007, 2009). The decay rates are, in reality, determined by biogeochemical processes, such as primary production, mineralization of organic matter, nitrogen fixation, denitrification, and hypoxia variations, which affect nutrient cycling. Gren, Savchuk and Jansson (2013) approximate decay rates by nutrient residence time. The nutrient transports among marine basins are described by transport matrices. All data described in this section can be found in the Appendix.

Cost functions were approximated for each country and basin using data on costs for different levels of load reductions from the programming model used in Elofsson (2000). The programming model includes data on abatement costs at the sources in different regions and countries, and their associated impact on the coastal load. Many of the abatement measures typically considered to reduce nutrient runoff are included, such as: increased nutrient cleaning capacity at sewage treatment plants, catalysts in cars and ships, flue gas cleaning in stationary combustion sources, reductions in fertilizer consumption and manure deposition, a change in spreading time of manure from autumn to spring, cultivation of catch crops, energy forests, and ley grasses, and creation of wetlands. When using the programming model to calculate costs for a certain load reduction, it is assumed that nitrogen and phosphorus are reduced separately. From the programming model, output is generated as pairwise combinations of load reductions and the associated minimum costs. These data are used to approximate a quadratic cost function, $c_{irt} = a_{ir}\left(\bar{Q}_{ir} - Q_{irt}\right) + b_{ir}\left(\bar{Q}_{ir} - Q_{irt}\right)^2$, which is estimated using OLS. The linear coefficient of this function was excluded when negative, in order to ensure that $c_{rit} > 0$ and $c'_{rit} > 0$ for all levels of load reductions, i.e. that cost functions obey standard assumptions. The estimated parameters of the cost functions can be found in the Appendix. The maximum reduction, which can be achieved by a certain region to a specific marine basin, is also obtained from the same programming model.

The choice of discount rate is important when costs are distributed over time. It is widely accepted that the discount rate should be based on individuals' preferences for present versus future consumption. When public expenses displace private investment, the possible opportunity cost of fund raising should be taken into account. For situations where the costs and benefits of a project or policy stretches of several generations, such as is often the case for environmental policies, there are different views on how the discount rate should be treated, e.g. by having the same, constant discount rate as for intra-generational policies in combination with directly addressing inter-generational issues through introduction of intergenerational weights in the social objective function (Moore et al., 2004). Based on the observation that future economic growth is more uncertain the further ahead in the future, it is also suggested that the discount rate should be lowered successively over time. However, lowering the discount rate over time through hyperbolic discounting implies dynamically inconsistent preferences (Laibson, 1997), wherefore we do not use this approach here in spite of the considerable time for the Baltic Sea to adjust to a change in nutrient loads. Boardman et al. (2003) suggest that a 3 percent discount rate is used for public projects, which is consistent with Weitzman's (2007) suggestion for a discount rate of 2-4 per cent for climate change. Weitzman (2007) motivates his estimate with the need to account for uncertainty about the future consequences of environmental degradation, which is relevant also in the case of the Baltic Sea. We assume that there is no displacement of private investment due to a Baltic Sea policy, which is motivated by the size of international capital markets where financial resources for the policy could be borrowed without any impact on the interest rate. Therefore, we do not take into account costs of fund raising, but follow Boardman (2003) and Weitzman (2007) by using a 3 percent discount rate.

Finally, we here describe the data used for the learning curve in equation (4), and the knowledge stock function in equation (5). Beginning with the learning curve, such curves for nutrient abatement measures are not available in the literature. Instead, most of the earlier work on learning curves deals with the energy sector. When controlling for the effect of R&D, Jamasb (2007) find a learning rate, which results from learning-by-doing, of between 0.48-41.5 per cent for different energy technologies. In a review of 77 different estimates of learning-by-doing rates, Kahouli-Brahmi (2008) finds learning rates varying between 1% and 41.5%. Rubin et al. (2004) estimate the learning-by-doing rates to 11% for sulphur dioxide and 12% for nitrogen oxide control technologies, and subsequently apply these estimates to the carbon capture and sequestration (CCS) technology to assess the learning potential for CCS and the associated reduction in costs of carbon mitigation. We follow the approach in Rubin et al. (2004) by extrapolating results from other technologies to that of nutrient abatement, assuming that the learning-by-doing rate is 3 percent, implying that $\mu = 0.044$, i.e. a relatively conservative rate.

With an exponential learning curve as described in equation (4), the impact of experience on abatement costs is very high for technologies that have not been applied earlier, or have only been applied to a very limited extent. For the Baltic Sea, policies to reduce nutrients have been applied for several decades, wherefore it is necessary to take this into account. We therefore follow Nemet (2006) and Marangoni and Tavoni (2013) by normalizing the knowledge capital stock with regard to the initial capital stock. We the have that

$$K_{frt} = \left(\text{cumulative abatement at time } t\right) / \left(\text{cumulative abatement at } t\text{=0}\right).$$

The cumulative abatement at time zero is calculated based on the difference in flow-normalized annual riverine loads of nutrients between the two periods 1997-2003 and 2006-2008. The percentage reduction between the two time periods is calculated from data in HELCOM (2011), and assumed to apply to the unregulated loads, see table A1 in the Appendix[1]. For all countries with zero reduction between the time periods, the initial knowledge stock is normalized to one for nitrogen and 0.01 for phosphorus. The so obtained initial knowledge stocks are available in table 1.

$\bar{K}_{fr0}$	Denmark	Estonia	Finland	Germany	Latvia	Lithuania	Poland	Russia	Sweden
kton N	50.5	1	1	6.3	1	17.2	1	1	13.3
kton P	0.42	0.11	0.04	0.14	0.01	2.1	1.93	6.06	1.44

Table 1. Knowledge stock at *t*=0, measured as cumulative abatement between 1997-2003 and 2006-2008.

Parameters defining the dispersal of knowledge among countries, β_{fg}, have been chosen based on the literature on international knowledge spillovers. In this literature, different factors have been identified as determinants of knowledge diffusion, and we therefore compare the outcome for several, alternative sets of β_{fg}. The first set is one where the knowledge stock is only built up within the own country, i.e. $\beta_{ff} = 1$ and $\beta_{fg} = 0$ for $\forall f \neq g$, similarly as assumed in Lindqvist and Gren (2013). This is also to some extent consistent with the conclusions in Bottazi and Peri (2003) in their study of the spillovers of R&D on the development of patents for European regions. They show that knowledge spillovers are highly localized and exist only within a distance of 300 km.

[1] It is assumed that the reductions have been made over seven years, and that they have increased linearly over time.

The second set of β_{fg} is based on the observation in Keller (2002) that technology spillovers drops by 50% for every 1200 km increase in distance. The estimate was derived for the impact of R&D expenditures on total factor productivity, and is here assumed to apply also for the dispersal of knowledge acquired through learning-by-doing. The distance between countries is measured as the flight distance between the capital cities, and the resulting β_{fg} matrix is found in table 2.

	Denmark	Estonia	Finland	Germany	Latvia	Lithuania	Poland	Russia	Sweden
Denmark	1.00	0.65	0.62	0.88	0.69	0.66	0.72	0.34	0.78
Estonia	0.65	1.00	0.95	0.53	0.86	0.77	0.66	0.63	0.84
Finland	0.62	0.95	1.00	0.50	0.81	0.72	0.62	0.61	0.83
Germany	0.88	0.53	0.50	1.00	0.60	0.58	0.69	0.25	0.65
Latvia	0.69	0.86	0.81	0.60	1.00	0.90	0.80	0.64	0.80
Lithuania	0.66	0.77	0.72	0.58	0.90	1.00	0.85	0.67	0.70
Poland	0.72	0.66	0.62	0.69	0.80	0.85	1.00	0.52	0.67
Russia	0.34	0.63	0.61	0.25	0.64	0.67	0.52	1.00	0.48
Sweden	0.78	0.84	0.83	0.65	0.80	0.70	0.67	0.48	1.00

Table 2. Knowledge diffusion, β_{fg} , determined by distance between countries. Impact of column country on row country.

Countries' total factor productivity depends not only on domestic R&D capital but also on foreign R&D capital, and the impact of foreign R&D capital is stronger the more open an economy is to foreign trade (Coe and Helpman, 1995). When estimating international knowledge diffusion, Coe and Helpman (1995) weigh foreign R&D by the fraction of imports from the foreign country in GDP. This general relationship between import shares and knowledge spillovers is also made use of in, e.g., van Meijl and van Tongeren (2004) with a purpose to investigate the role of knowledge spillovers for GMO adoption. Here, we follow the same logic, by calculating β_{fg} as the value of agricultural products imports from the foreign country g relative to the total value of agricultural production in the domestic country f. Values of agricultural import and production are chosen because of the large importance of this sector for nutrient reductions to the Baltic Sea (Gren et al., 1997; Elofsson, 2010; Wulff et al., 2014). Data on agricultural import and production value has been obtained from the FAOSTAT database for 2011. It is assumed that β_{ff} =1, and the calculations give $\beta_{fg} < 0$ for $\forall f \neq g$, see table 3. With knowledge spillovers calculated this way, there is thus a larger impact of one country on another if it is more dependent on agricultural food imports from that country.

The level of human capital is argued to facilitate the adoption of new technologies (Keller, 2004; Eaton and Kortum, 1996; Xu, 2000). Similarly as most studies investigating the role of human capital for knowledge diffusion, we use educational attainment in the adult population as a measure of human capital, for which data have been obtained from Barro and Lee (2014). Given our focus on distributional effects, our main interest is in the relative ability to absorb new knowledge. We therefore normalize β_{fg} to one for the country i with the highest educational attainment, and calculate β_{fg} for the other countries as the proportional level of educational attainment, compared to the country with the highest level, see table 4. There are small differences in educational attainment across the Baltic Sea countries, implying that there would be small differences in knowledge dispersal parameter which is consistent with the observation in Eaton and Kortum (1996) that there are modest differences in the impact of R&D on domestic productivity compared to that on productivity abroad.

	Denmark	Estonia	Finland	Germany	Latvia	Lithuania	Poland	Russian	Sweden
Denmark	1.00	0.00	0.01	0.26	0.00	0.01	0.03	0.00	0.09
Estonia	0.06	1.00	0.18	0.13	0.23	0.17	0.11	0.02	0.06
Finland	0.09	0.04	1.00	0.21	0.01	0.02	0.04	0.01	0.18
Germany	0.06	0.00	0.00	1.00	0.00	0.00	0.05	0.00	0.01
Latvia	0.06	0.14	0.02	0.13	1.00	0.40	0.16	0.05	0.01
Lithuania	0.04	0.06	0.01	0.11	0.13	1.00	0.18	0.03	0.01
Poland	0.03	0.00	0.00	0.16	0.00	0.01	1.00	0.00	0.00
Russian	0.01	0.00	0.01	0.02	0.00	0.00	0.01	1.00	0.00
Sweden	0.39	0.01	0.07	0.32	0.00	0.02	0.06	0.00	1.00

Table 3. Knowledge diffusion, β_{ijr}, determined by import patterns. Impact of column country on row country.

	Denmark	Estonia	Finland	Germany	Latvia	Lithuania	Poland	Russia	Sweden
Average years of schooling in population 15+ in year 2010	9.97	11.77	9.96	11.82	10.42	10.79	9.84	11.48	11.48
β_{fg} based on human capital	0.85	1	0.85	1	0.89	0.92	0.84	0.98	0.98

Table 4. Knowledge diffusion, β_{fg}, determined by human capital. Impact of column country on row country.

Results

In the following, we first investigate how knowledge diffusion across countries affects total net present cost and total abatement, and the distribution of costs and abatement across countries. This is done comparing five different scenarios, which differ only in assumptions made about the magnitude of knowledge diffusion between countries. First, we have two scenarios beta=0, beta(f,f)=1, referring to the cases when there is no learning-by-doing at all and only domestic learning, respectively. Second, we also look the cases when knowledge diffusion instead depends on distance, imports and human capital, denoted by beta=DIST, beta=IMP and beta=HUM, respectively.

We then compare the role that the two different diffusion processes described above, i.e. diffusion of knowledge between different countries, and diffusion of nutrients between different marine basins, play for total costs and the distribution of costs across countries. For this investigation three different scenarios are compared, which differ in assumptions made about parameters for the two diffusion processes. In these scenarios, beta=0 indicates zero learning-by-doing, beta(f,f)=1 indicates only domestic learning by doing and zero knowledge diffusion between countries, beta=DIST indicates that knowledge diffusion is assumed to be proportional to distance between countries. For nitrogen transport among marine basins, alfa=DEF indicates that default values for nitrogen transports are used and alfa=1/0 indicates that all emission stay in the basin to which they are emitted, i.e. diagonal elements of transport matrix equal one, and off-diagonal elements equal zero. The different scenarios are summarized in Table 5.

Scenarios for investigation of assumptions about knowledge diffusion		**Scenarios for investigation of the relative importance of knowledge and marine diffusion**	
No learning by doing	beta=0	No learning by doing & default parameters for marine diffusion between basins	beta=0, alfa=DEF
Only domestic learning by doing	beta(f,f)=1	No learning by doing & all emission remain in the basin to which they are emitted	beta=0, alfa=1/0
Knowledge diffusion between countries proportional to distance	beta=DIST	Only domestic learning by doing & default parameters for marine diffusion between basins	beta(f,f)=1, alfa=DEF
Knowledge diffusion between countries proportional imports	beta=IMP	Only domestic learning by doing & all emission remain in the basin to which they are emitted	beta(f,f)=1, alfa=1/0
Knowledge diffusion between countries proportional to human capital	beta=HUM	Knowledge diffusion between countries proportional to distance & default parameters for marine diffusion between basisn	beta=DIST, alfa=DEF
		Knowledge diffusion between countries proportional to distance & all emission remain in the basin to which they are emitted	beta=DIST, alfa=1/0

Table 5. Scenarios in the numerical calculations.

The role of knowledge diffusion for abatement costs

How are costs and nutrient abatement, and the distribution of those across countries, affected by knowledge diffusion between countries? First, as can be seen in Fig. 1, already domestic learning-by-doing from experience in the own country, i.e. beta(f.f) =1*,* has a considerable impact on total net present cost, reducing it by 16 percent. Compared to the case with only domestic learning-by-doing, knowledge diffusion between countries further reduces the net present cost by 1-8 percent, depending on the set of parameters chosen for cross-country knowledge diffusion. The smallest impact on net present costs occurs if knowledge is assumed to be embodied in imports, as this is linked to lower values of the diffusion parameters. The larger impact on net present cost, 8 percent, is achieved when knowledge diffusion is assumed to be proportional to either distance or to human capital. The impact is approximately equally large in the two latter cases in spite of the diffusion parameters have a considerably larger value on average when assumed to mirror human capital. The reason is that the human capital-based parameter affects not only accumulation foreign knowledge but also accumulation of knowledge from domestic abatement. Lower accumulation of knowledge from domestic abatement then counteracts the effect of larger knowledge diffusion between countries.

Poland carries a large share of the abatement cost under cost-effectiveness, independently of assumptions made about learning rate and knowledge diffusion, similarly as shown in earlier studies (Gren, Elofsson and Jannke, 1997; Elofsson, 2010), see Fig. A1 in the Appendix. Under solely domestic learning-by-doing the unit cost of Polish abatement falls considerably due to the large abatement carried out in the country. This implies that Poland increases its share in total abatement.

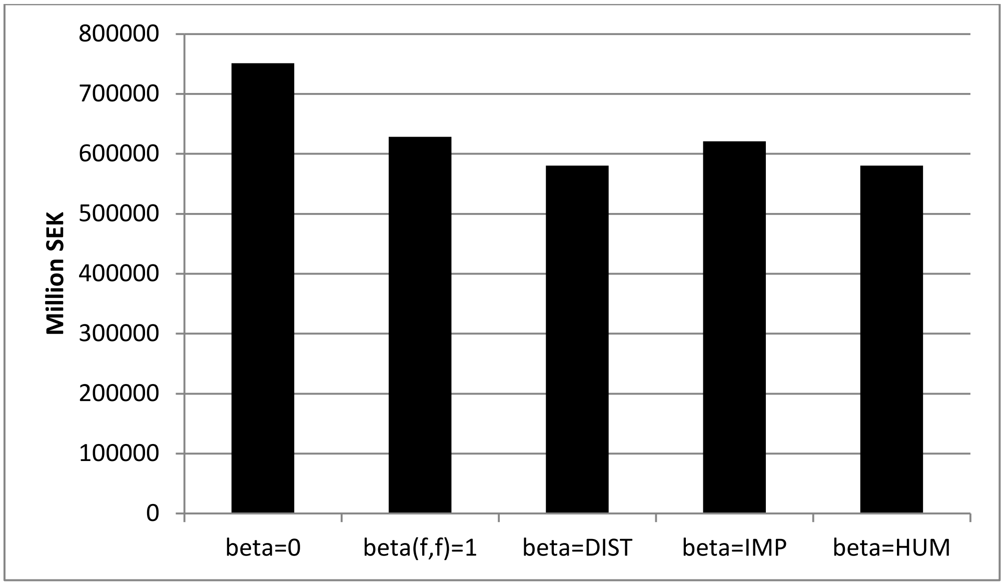

Fig. 1. Total net present cost under different assumption about knowledge diffusion.

With knowledge diffusion between countries, costs fall in all countries compared to a situation where there is only domestic learning, see Fig. 2 below. When knowledge diffusion between countries is assumed proportional to distance, the reduction in costs is relatively similar in all countries. The impact on costs in a given country is determined by its distance from countries which abate much nutrients and the shape of the cost functions in the countries, as discussed above. Costs fall the most in Latvia and the least in Germany and Russia. Latvia is centrally located in the drainage basin, close to countries with major quantities of nutrients being abated, such as Poland and Russia. Substantially lower costs in Latvia are associated with a large increase of phosphorus abatement, suggesting that the changes in abatement in Latvia are explained mainly by the impact of other countries on Latvia, and not *vice versa*. Germany and Russia are located at a larger distance from the center of the catchment, implying a lower impact on costs in these countries from abatement made in other countries, as well as the opposite.

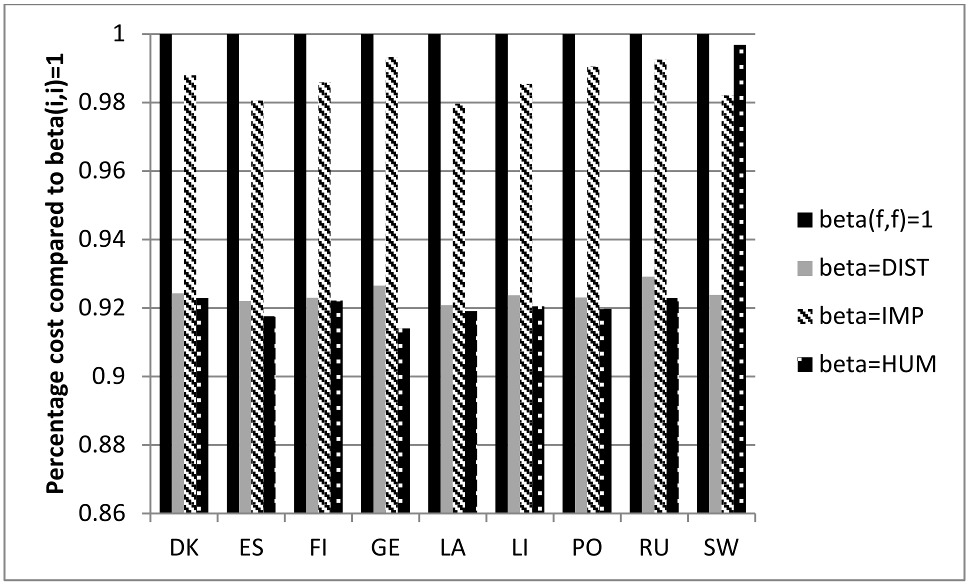

Fig. 2. Net present cost in different countries, as percentage of net present cost with only domestic learning, under different assumptions about knowledge diffusion.

In the scenario where knowledge diffusion is proportional to imports, the impact on total costs is smaller, but impact on the cost allocation is larger, compared to the case when knowledge diffusion is proportional to distance. Compared to the case with no knowledge diffusion, the largest cost reduction occurs in Estonia and Latvia, and is explained by their relatively large dependence on agricultural imports from Poland, and therefore comparatively large knowledge transfer from this country which is a major abater. The smallest impact on costs is found in Germany and Russia, both of which are little dependent on agricultural imports from other countries in the Baltic Sea drainage basin, and hence receive little knowledge embodied in imports. Albeit the German knowledge stock is little affected by other countries in this scenario, abatement in Germany has a comparatively large impact on knowledge stocks in other countries, given the considerable exports from Germany to several other countries in the catchment. Again, it thus seems that “being–impacted–by” is more important than “having–an–impact-on”, i.e. knowledge transfer is mainly important for the impact on cost levels in the different countries as well as in total, but implies only small changes of the allocation of abatement which are motivated by the associated increase in knowledge diffusion. This has similar to the observation made in studies which investigate only domestic learning-by-doing and its impact on the abatement path over time (Goulder and Mathai, 2000; Rasmussen, 2001). However, a difference here is that the impact on the cost level differs across countries, implying a change in the allocation of abatement and the associated cost.

The role of knowledge diffusion for abatement quantity

The cost-effective, aggregate abatement of the two nutrients, i.e. the total abatement over all time periods, can be higher or lower when knowledge diffusion is taken into account, see Fig. 3. There are two reasons why aggregate abatement is affected by knowledge dispersal, one of those is the reallocation of abatement in time, and the other the reallocation across space. The net effect is determined by empirical factors.

The impact on aggregate abatement is small in all investigated scenarios. For nitrogen, the aggregate abatement is higher in all scenarios with knowledge diffusion, compared to the case with only domestic abatement. First, with knowledge diffusion, more of the nitrogen abatement is allocated to Poland. This tends to reduce aggregate abatement, because abatement of emissions directly to the Baltic Proper basin have a larger impact on the nitrogen stocks in that basin compared to abatement made to basins further away. However, in the presence of international knowledge diffusion there are also larger benefits from early abatement, because early abatement reduces abatement costs in later periods also in other countries than the home country. This implies that with international knowledge diffusion, more nitrogen abatement is done earlier in time. This early abatement has a smaller impact on the nitrogen stock at time T compared to abatement carried out in later time periods, implying that in total more nitrogen abatement must be carried out. For nitrogen, the latter effect outweighs the former.

For phosphorus, the effect is similar as that for nitrogen if knowledge diffusion is proportional to distance or imports, i.e. the tendency towards more early abatement outweighs that of the increased concentration of abatement to Poland. If, instead, knowledge diffusion is proportional to human capital less abatement is carried out in total. There is no significant difference in the allocation in abatement over time between different scenarios. Instead, the lower aggregate abatement when knowledge diffusion is assumed proportional to human capital is explained by a reallocation in space. In particular, costly phosphorus reductions in Swedish catchments, other than that which drains to the Baltic Proper, are reduced and replaced by further reductions in countries emitting directly to the Baltic Proper. This is explained by the considerably higher international diffusion of knowledge in combination with the lower domestic learning which implies that cost reductions occur more uniformly across all countries compared to the other scenarios.

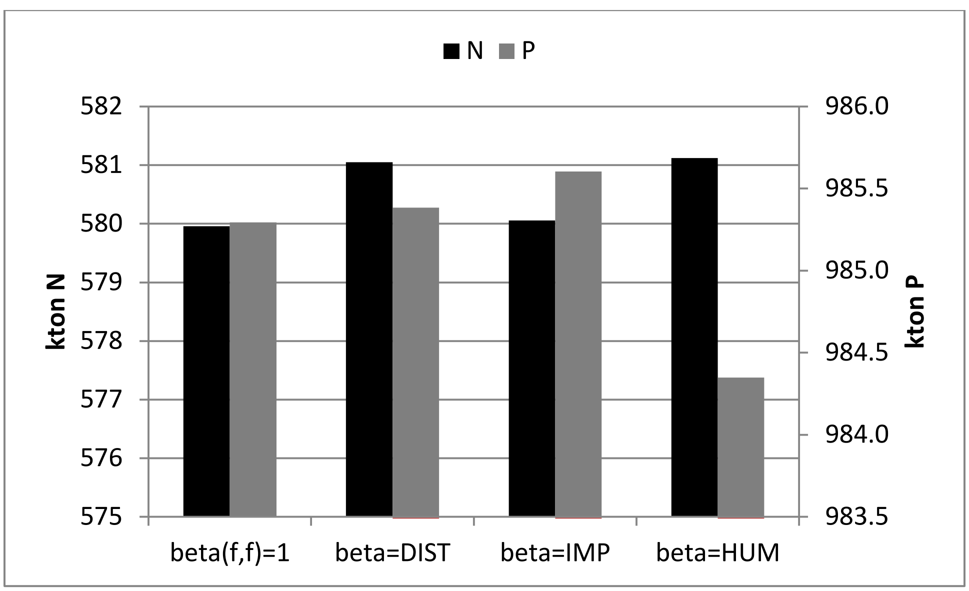

Fig. 3. Aggregate abatement of N and P emissions in kton under different assumptions about knowledge dispersal.

The role of marine nutrient transports vs knowledge diffusion

Two different diffusion processes are considered in the above described model, diffusion of knowledge between countries and diffusion of nutrients between marine basins. Figure 4 compares the sensitivity of net present costs to assumptions made about the two different dispersal processes. It shows that if it is incorrectly assumed that emissions only affect nutrient stocks in the basin to which they are emitted (i.e. alfa(f,f)=1) will lead to the conclusion that net present abatement costs are only half of what they would be, had nutrient dispersal between basins been correctly accounted for. This can be seen as the bars to the right in Fig. 4 are only half of those to the left. Compared to that, assumptions made about learning and knowledge dispersal has a smaller, but still considerable impact on the net present cost. Only domestic learning reduces net present cost by about 16%, while learning in combination with knowledge dispersal reduces net present cost by 22%, compared to the case with zero learning. The impact on net present cost is similar in relative terms independently of assumptions made about marine nutrient dispersal.

Assumptions about the two diffusion processes affect the allocation of abatement and cost in time and space. If there is diffusion of knowledge this can, in principle, imply that cost-effective abatement becomes spatially more or less concentrated compared to the case without knowledge diffusion. For the Baltic Sea, there is a clear tendency towards more spatially concentrated abatement. The reason is that learning-by-doing implies a scale advantage in abatement. If one country already abates more than other countries, even more of the abatement will be allocated to this country if there is learning-by-doing. Knowledge spillovers generally enhance this effect, i.e. lead to a higher concentration of abatement as long as diffusion to/from that country is not substantially lower than for other countries. The concentration effect can however be smaller or even zero if the large abater's marginal cost curve increases rapidly in the interval of interest. When there is marine diffusion of nutrients between basins, this generally implies that the cost-efficient abatement is distributed over space to larger extent compared to when this is not the case.

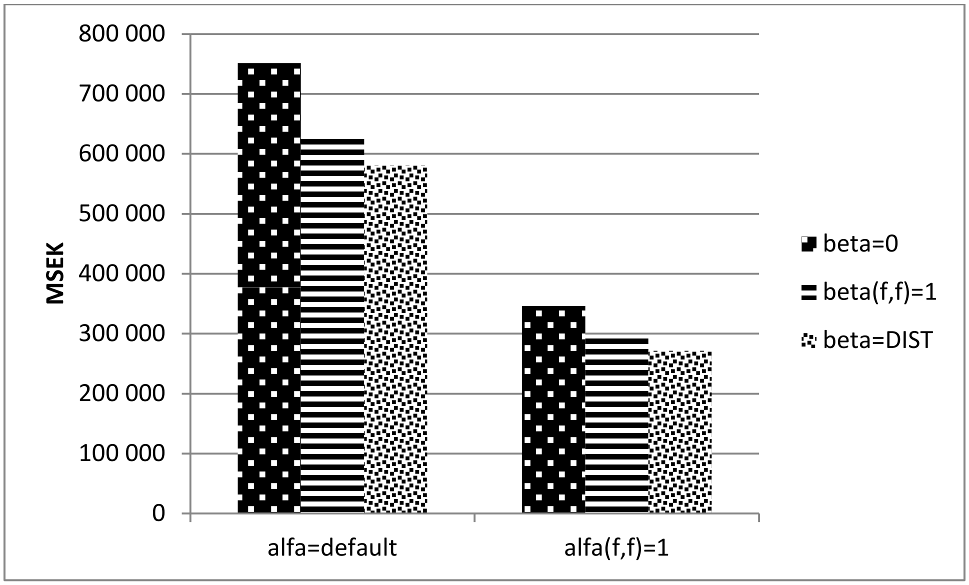

Fig. 4. Sensitivity of net present cost to assumptions about marine nutrient dispersal, learning and diffusion of knowledge.

The effect of learning-by-doing on the timing of abatement is known to be ambiguous. Early abatement increases the knowledge stock and reduces the cost of all future abatement, implying that early abatement can be cost-effective. On the other hand, knowing that the future abatement costs will be lower than current abatement costs implies that it can be cost-effective to postpone abatement. Which of these two effects will dominate is an empirical matter (Goulder and Mathai, 2000; Rasmussen, 2001). However, earlier studies suggest that the timing of abatement is little affected by learning-by-doing and that instead, the major effect is the impact on the cost level (Goulder and Mathai, 2000). Intuitively, this should hold also when there is knowledge diffusion between countries. On the other hand, if there is diffusion of nutrients between different marine basins, more abatement is undertaken further away from the target basin under cost-effectiveness. Intuitively, this should imply that abatement would have to be carried out earlier. However, this is not captured by the above described model as dispersal between basins is assumed to occur instantaneously.

Fig. 5 below shows the percentage of the net present costs incurred in the first 10 years for the different scenarios in Table 5. The smallest cost share in the early phase of the policy period can be found in the scenario with zero learning and when emissions only affect the basin to which they are emitted. The share of total cost in this scenario is approximately half of that in the scenarios with default data on marine dispersal and either only domestic learning or knowledge dispersal proportionate to distance. As Fig. 5 shows, results obtained from the model suggest that learning-by-doing leads to a higher share of abatement costs being allocated to earlier time periods, whereas if emissions affect only the marine basin to which they are emitted, the abatement costs are delayed.

To further understand the timing of abatement, we also look at the share of net present costs allocated to the last 10 time periods, see Fig. 6. This Figure shows that relatively larger costs are incurred closer to the final date if there is no learning-by-doing, and that knowledge spillovers do not affect the time path compared to only domestic learning-by-doing. There are also relatively smaller costs in the last time periods in the scenarios where emissions only affect the receiving basin. The latter is explained by a larger share of costs being allocated to intermediate time periods. This can be explained as follows. In all scenarios, there is a tendency towards postponement of abatement costs, explained by discounting of future costs. This postponement can go on for a longer time if emissions only affect the “home” basin than when there is dispersal because emission reductions are then assumed to have a larger impact on nutrient concentrations in the “home” basin. However, at a certain point in time, it becomes necessary to rapidly increase abatement to a high level in order to meet the nutrient concentration targets in the target year. This point in time occurs earlier when only reductions around the “home” basin are assumed to have an impact, given that close to the maximum abatement potential has to be used to meet the target. Summing up, if there is learning and knowledge dispersal, this tends to imply larger early abatement efforts albeit the impact on timing is modest. If there is nutrient dispersal between marine basins, this implies that abatement costs are more evenly distributed over time than would be the case without such dispersal.

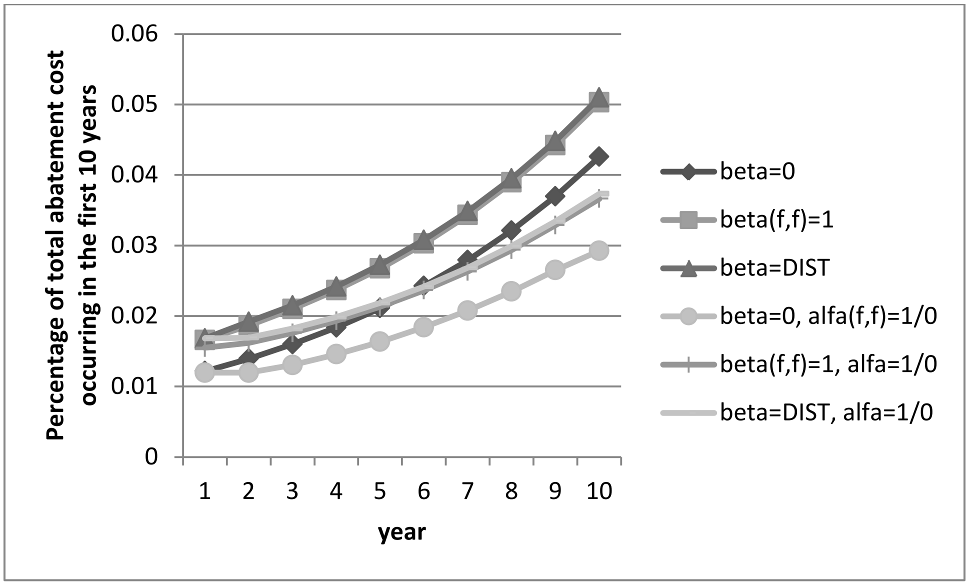

Fig. 5. Abatement cost, percentage of total cost, in first ten years.

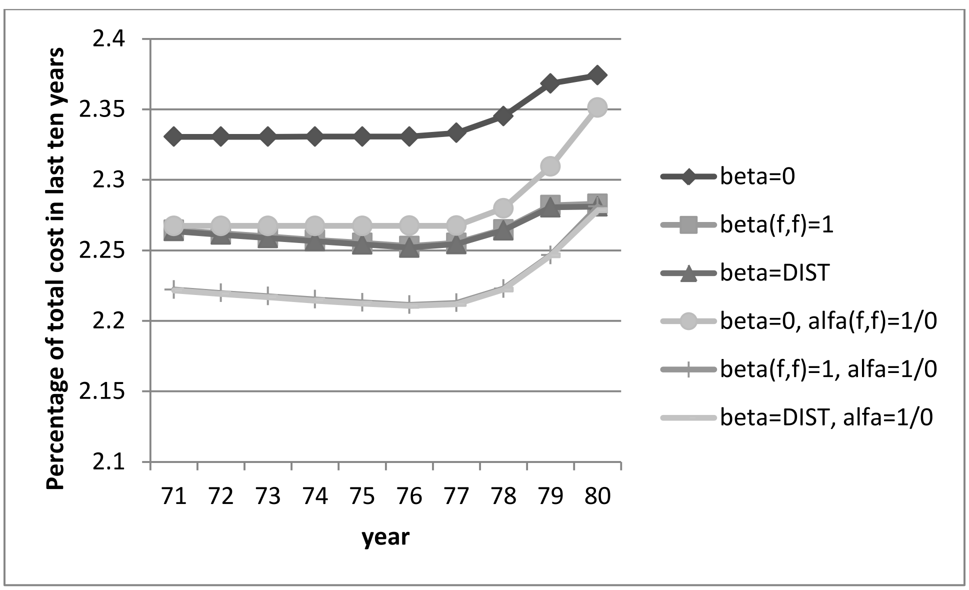

Fig. 6. Abatement cost, percentage of total cost, in last ten years.

Assumptions regarding the two diffusion processes, knowledge and marine nutrient dispersal, have different impact on the allocation of abatement costs between countries, Fig. 7 shows assuming that emissions only affect the receiving basin (alfa=1/0) has a significantly larger effect on the allocation of costs between countries than assuming that there is learning-by-doing and dispersal of knowledge. This is not surprising given that such an assumption about marine dispersal excludes abatement in a large part of the Baltic Sea drainage basin. If emissions would only affect the receiving basin (alfa=1/0), but have a larger impact on that basin, total net present cost would thus be much lower, but also more unequally distributed among countries, as all efforts would be allocated to countries that emit directly to the target basin, in particular to those which only emit to the target basin, i.e. Poland and Lithuania. Compared to that, assumptions about knowledge dispersal have a very modest impact on the distribution of costs.

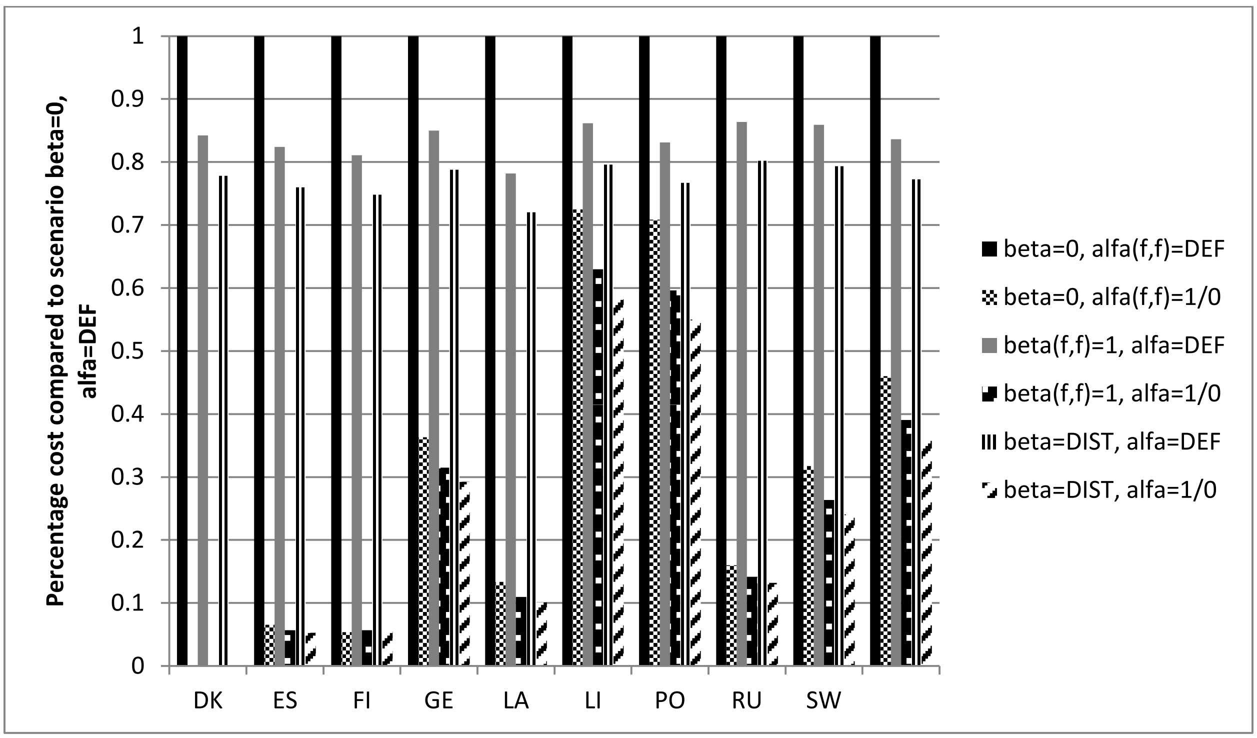

Fig. 7. Percentage cost under different scenarios compared to the case with no learning-by-doing and default marine transports.

Discussion and conclusions

Increased experience with abatement technologies in the home country and abroad can reduce future costs of their use. The purpose of this paper is to investigate the implications of international knowledge diffusion for the costs of Baltic-wide policy to reduce nutrient concentrations in the Baltic Sea. The effect of international knowledge diffusion on the distribution of abatement and costs over time and space is analyzed and compared to the effect of nutrient diffusion between different marine basins. To this end, a numerical, dynamic cost-effectiveness model covering the Baltic Sea drainage basin is used. The novelty of the study is the analysis of knowledge dispersal and its role for a cost-effective policy to reduce nutrient pollution.

The analysis shows that the cost-effective abatement choices are determined not only by the impact of the abatement on nutrient emissions and concentration, and the costs incurred, but also by the potential of the abatement to add to the stock of experience in the domestic country as well as abroad. In a hypothetical situation, this could imply that abatement can be cost-effective even though costs are comparatively high, and the impact on water quality low, provided that the abatement contributes much enough to abatement knowledge stocks. However, more plausible is that compared to a situation where there is no knowledge dispersal between countries, knowledge dispersal will lead to a further concentration of abatement to countries with large, low-cost abatement opportunities, unless the knowledge stock in these countries is unaffected by abatement experiences made in other countries.

Earlier research suggests that knowledge diffusion between countries is related to the distance between countries, countries' openness to trade, and human capital. The relative importance of these factors is not well known. The empirical analysis in this paper shows that it matters which one of these factors is assumed to determine knowledge diffusion. If knowledge diffusion is associated to distance, this has a smaller impact on the distribution of costs and abatement than if it is associated with imports or human capital. When comparing the consequences of knowledge diffusion between countries and diffusion of nutrients between marine basins, the results show that learning and knowledge diffusion tends to motivate larger early abatements efforts, compared to a situation without these processes. False beliefs regarding the dispersal of nutrients, e.g. believing that nutrient have a strong impact on the basin to which they are emitted, but no impact on other basins, would lead a policy-maker to postpone abatement, but that in medium term rapidly increase abatement to levels close to the maximum potential. This contrasts with the smoother development of the abatement path in the presence of knowledge diffusion.

Whereas this study provides further understanding of the role of knowledge diffusion for an international cost-effective policy for abatement of stock pollutants, there are several limitations to the analysis. These limitations include uncertainty about learning rates for technologies to reduce nutrient pollution and about the magnitude of international knowledge spillovers associated with experience of pollution abatement. Moreover, the study does not take into account the role of technological innovation as another determinant of future pollution abatement cost. Further research in these areas would improve the understanding of knowledge in relation to pollution abatement costs.

There are several policy implications from the study. First, it suggests that larger early abatement efforts can be motivated by their role for increasing experience, and hence reducing future costs, compared to what is suggested in studies that ignore the role of learning and knowledge diffusion, such as Gren, Savchuk and Jansson (2013), Laukkanen and Huhtala (2008) and Ahlvik et al. (2014). However, internationally agreed policies for the Baltic Sea build on the presumption of even larger early abatement efforts, given that they are based on the idea that a fixed level on nutrient reductions should be made in every year. The resulting emission level should then lead to the desired nutrient concentration in the Sea in the long run, albeit there is no explicit restriction on how long time should be allowed until the targeted nutrient concentration is actually achieved (HELCOM, 2007). Such a policy is likely to imply higher costs that the one analyzed in this paper, while there is also a risk that the target is met at a later date. Moreover, and perhaps contrasting to expectation, the study shows that if there is knowledge diffusion, this further strengthens the concentration of abatement efforts to Poland under a cost-effective policy scheme. This confirms and strengthens the conclusion regarding Poland's role in this context (Gren, Elofsson and Jannke, 1997; Markowska and Zylicz, 1999; Elofsson, 2010; Wulff et al., 2014; Hasler et al., 2014), pointing to the need to solve the cost distribution problem that arises as a consequence of the large Polish abatement burden. Finally, the study shows that the role of individual countries in a cost-effective abatement scheme depends on whether other countries will also engage in abatement and on whether there is a high degree of spillover and transferability of learning across countries. Consequently, internationally policies supporting nutrient pollution abatement, such as agri-environmental schemes within the EU rural development programs, should take into account the potential for learning and dispersal of knowledge through prioritization of measures and regions.

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APPENDIX

Table A1. Unregulated loads of bioavailable nutrients, measured as contemporary load 1997–2003 [1].

	Denmark	Estonia	Finland	Germany	Latvia	Lithuania	Poland	Russia	Sweden	Total
N, kton/year	69.7	23.6	50.4	57.3	55.2	40.2	190.1	59.5	88.8	634.8
P, kton/year	1.7	1.2	3.2	0.5	2.1	2.4	13	6.1	3.7	33.8

[1] Gren, Jansson and Savchuk (2013).

Table A2. Nutrient stocks, decay rates*, and BSAP nutrient pool targets for sea basins.

	Nitrogen				**Phosphorus**			
Marine basin	**Initial annual load, kton**	**Initial nutrient stock, kton**	**Decay rate,%**	**BSAP nutrient pool target, kton**	**Initial annual load, kton**	**Initial nutrient stock, kton**	**Decay rate,%**	**BSAP nutrient pool target, kton**
Bothnian Bay	28	183	0.153	183	2.4	7.4	0.324	7.4
Bothnian Sea	46	457	0.100	457	2.3	71.2	0.042	71.2
Baltic Proper	309	1,330	0.232	1,142	17.8	434.6	0.041	217.7
Gulf of Finland	74	143	0.517	143	6.4	25.9	0.247	17.4
Gulf of Riga	59	86	0.691	86	2.1	12.7	0.165	8.4
The Sound	55	34	1.000	29.2	1.3	6.7	0.201	6.7
Kattegat	64	55	1.000	50.7	1.5	8.7	0.173	8.7

* Decay rates are calibrated such that initial nutrient stocks are steady state stocks for the given initial nutrient loads. This requires a further assumption that there is an immediate decay of all nitrogen reaching the Sound and Kattegat, equal to 0.382, and 0.139, respectively.

Table A3. Coefficients for nitrogen transports among marine basins, from column basins into row basins for biologically available nitrogen.

	Bothnian Bay	Bothnian Sea	Baltic Proper	Gulf of Finland	Gulf of Riga	The Sound	Kattegat
Bothnian Bay	0.391	0.047	0.041	0.012	0.009	0.008	0.008
Bothnian Sea	0.297	0.491	0.032	0.033	0.03	0.017	
Baltic Proper	0.242	0.346	0.727	0.362	0.31	0.213	0.075
Gulf of Finland	0.017	0.027	0.099	0.512	0.029	0.022	0.016
Gulf of Riga	0.008	0.015	0.07	0.02	0.566	0.014	0.013
The Sound	0.03	0.051	0.036	0.044	0.04	0.481	0.133
Kattegat	0.011	0.019		0.011	0.011	0.239	0.752

Source: Gren, Savchuk and Jansson (2013). Nutrient transport coefficients are calibrated to such that initial input to each basin, see table A2 is achieved with the given initial load from each country, see table A1.

Table A4. Coefficients for phosphorus transports among marine basins, from column basins into row basins for biologically available nitrogen.

	Bothnian Bay	Bothnian Sea	Baltic Proper	Gulf of Finland	Gulf of Riga	The Sound	Kattegat
Bothnian Bay	0.486	0.035	0.05	0.023	0.014	0.01	0.006
Bothnian Sea	0.167	0.328	0.02	0.068	0.101	0.069	0.027
Baltic Proper	0.208	0.356	0.689	0.434	0.388	0.262	0.138
Gulf of Finland	0.045	0.063	0.219	0.312	0.066	0.045	0.029
Gulf of Riga	0.015	0.02	0.076	0.034	0.199	0.014	0.01
The Sound	0.022	0.099		0.011	0.124	0.363	0.152
Kattegat	0.011	0.056		0.002	0.071	0.213	0.61

Source: Gren, Savchuk and Jansson (2013). Nutrient transport coefficients are calibrated to such that initial input to each basin, see table A2 is achieved with the given initial load from each country, see table A1.

Table A5. Coefficients of cost functions in MSEK and kton, standard error within parenthesis.

	Nitrogen	Nitrogen	Nitrogen	Nitrogen	Phosphorus	Phosphorus	Phosphorus	Phosphorus
	a_{ir}	b_{ir}	Adj R2	Max red. (% of BAU)	a_{ir}	b_{ir}	Adj R2	Max red. (% of BAU)
Denmark								
The Sound	--	21.37 (0.48)	0.91	50	--	3609 (93)	0.92	50
Kattegat	--	40.93 (0.48)	0.92	40	--	21433 (2250)	0.8	40
Estonia								
Baltic Proper	43.62 (0.98)	17.20 (1.89)	0.92	50	486 (249)	154925 (10423)	0.87	30
Gulf of Finland	47.66 (1.14)	1.17 (0.22)	0.92	50	--	6829 (166)	0.92	50
Gulf of Riga	31.52 (7.27)	9.68 (2.05)	0.91	50	566 (152)	23583 (1912)	0.92	50
Finland								
Bothnian Bay	156.03 (9.18)	21.33 (2.02)	0.92	50	--	14625 (707)	0.9	50
Bothnian Sea	72.10 (10.54)	32.43 (2.35)	0.92	50	--	6468 (139)	0.92	50
Gulf of Finland	--	19.61 (1.18)	0.88	50	--	3550 (130)	0.91	50
Germany								
Baltic Proper	--	11.32 (0.46)	0.91	50	394 (16)	1061 (204)	0.92	50
The Sound	56.07 (14.55)	35.26 (4.87)	0.91	50	261 (36)	2838 (304)	0.92	50
Latvia								
Baltic Proper	56.07 (14.55)	35.26 (4.87)	0.91	45	1721 (108)	11119 (901)	0.92	50
Gulf of Riga	92.77 (5.92)	3.52 (0.33)	0.92	50	1870 (122)	1524 (171)	0.92	50

Lithuania	11.79 (0.86)	0.34 (0.06)	0.92	50	307 (70)	1491 (74)	0.92	50
Poland	8.05 (0.80)	0.04 (0.01)	0.92	50	305 (194)	472 (49)	0.91	50
Russia								
Baltic Proper	154.51 (3.52)	7.46 (0.80)	0.92	50	--	13381 (135)	0.9	35
Gulf of Finland	174.30 (6.88)	2.83 (0.38)	0.92	50	--	2565 -120	0.89	40
Sweden								
Bothnian Bay	85.77 (8.88)	314.31 (12.86)	0.67	15	2442*	--	--	5
Bothnian Sea	105.36 (73.31)	66.46 (25.22)	0.78	20	--	23326 (2107)	0.72	15
Baltic Proper	184.39 (9.27)	10.21 (0.93)	0.91	43	--	7620 (402)	0.87	35
The Sound	36.98 (2.14)	11.62 (1.07)	0.92	50	171 (62)	16519 (1549)	0.92	50
Kattegat	129.35 (5.38)	10.91 (0.69)	0.89	35	--	10565 (690)	0.87	45

*based on single observation due to very low abatement capacity

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