Evaluating the effect of climate variation on the cost efficiency of a crop permit policy in Southern Sweden

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ABSTRACT

Current international agreements call for a significant reduction of nitrogen loads to the Baltic Sea. New measures to reduce nitrogen loads from the agricultural sector and an increased focus on cost efficiency will be needed to meet reduction targets. For policy design and evaluation it is important to understand the impact of weather on the efficiency of abatement measures. One new proposed policy is the use of crop permits based on weather normalized average leaching. This paper describes the use of the Spearman method to determine the efficiency of this policy with annual weather variation. The conclusion is that the values of the Spearman correlation coefficients in the study indicate that using average leaching for the individual crops on specific soil types for calculating crop permit requirements is an efficient policy. The Spearman method is demonstrated to be a simple useful tool for evaluating the impact of weather and is recommended for use in new studies.

Key words | crop permits, eutrophication, nitrogen abatement measures, Spearman

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INTRODUCTION

Mobilization and transport of nutrients from terrestrial systems to rivers, lakes and marine environments contribute to deteriorating water quality and eutrophication. There are a number of policy initiatives in place which are meant to reduce nutrient loads. For example, the Swedish government is committed as a signatory to the Baltic Sea Action Plan (BSAP) to reduce nitrogen loads to the Baltic Sea by 21,000 tons and phosphorus loads by 291 tons to achieve good environmental status by 2021 (SNV 2008). However, there is increasing concern about the costs of achieving water quality goals (Shortle *et al*. 2012).

The EU's Water Framework Directive (WFD) (2000/60/EC), which strengthens the options for protecting water quality, 'emphasizes the need to use price policy, safeguarding of the polluter-pays principle and the endeavors to achieve the targets cost-effectively.' (SNV 2008, p. 22). The need for cost effective measures is also emphasized in a recent report on the design and management of agri-environment support programs financed by EU member states (European Court of Auditors 2011). In their conclusions the report authors recommend that agri-environmental expenditures should be more precisely targeted and that the Member States should be more proactive in managing agri-environment payments. Environmental and economic effects of measures need to be evaluated to both reduce nitrogen and phosphorus loads to meet the demands of the BSAP and the WFD as well as improve the cost efficiency of agri-environmental support programs.

Edge of the field nitrogen losses from agricultural production depend on a number of local site specific factors including crop type, soil type, cultivation, fertilization programs and climate. Of these five factors three can be managed (crop type, cultivation and fertilization) while two depend on conditions outside the control of management. For design of economic policy and implementation with a focus on targeting it is important to understand how the interaction between management choices and natural conditions affect the leaching of nitrogen. The purpose of this study is to present a method for studying one of these relationships, the variation in weather, and to evaluate

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how this variation impacts on the cost effectiveness of a proposed innovative policy that includes targeting.

The paper begins with a description of a proposed policy to reduce nutrient loads to the Baltic Sea, a requirement for crop permits based on expected nitrogen losses (Collentine & Johnsson 2012). The cost effectiveness of this policy depends on model generated leaching losses. In the policy analysis by Collentine & Johnsson (2012), leaching coefficients are used to estimate the effect and cost effectiveness of the proposed policy. The leaching coefficients in the analysis are calculated for major crop types with the SOILNDB program using a 20-year series of actual weather for specific production areas in Sweden (Johnsson *et al.* 2008). The leaching coefficients from this normalized set of weather data represent average leaching based on weather for the area but independent of individual years. However, it is very important to study how effective this type of policy would be when there is annual variation for weather as there may be a great deal of variation in calculated losses with respect to crop and soil type. This becomes even more important as climate change is expected to increase the variation in precipitation and temperature in the Baltic Sea area of Northern Europe (Meier 2006; Meier *et al.* 2012).

The following section of the paper uses a statistical method, the Spearman's rank correlation coefficient, for appraising the stability of the relationship between leaching and annual sets of weather data for a production area in Southern Sweden. The application uses the Spearman method to evaluate modeled leaching from the SOILNDB model for the three major soil types and four major crops in the study area. The final section of the paper discusses the results of the application and suggests areas for further research.

BACKGROUND

Since nitrogen (N) losses from agriculture are sensitive to weather conditions there is a need for studies that evaluate the cost effectiveness of abatement policy under various climate scenarios. Lacroix *et al.* (2005) observed that, with respect to nitrogen abatement policy, 'efficiency conditions have not been precisely assessed' and more specifically that 'uncertainty and climate variability have not been significantly explored' (p. 115). Lacroix *et al.* (2005) perform a study using bio-physical modeling of the between-year effects to study the cost effectiveness of six abatement policies in use in the EU. The purpose of their study is to evaluate *ex post* which policy mix would have been the least cost alternative to reach a fixed environmental target under a set of climate scenarios. What Lacroix *et al.* (2005) compare is the effectiveness of policy alternatives. They do not evaluate how these policies perform if average effects are compared to annual effects because none of the six policies in the study are based on cropping choices and expected losses from individual crops.

Gren (2010) and Elofsson (2011) also evaluate the effect of climate change on the cost effectiveness of agricultural abatement measures. Gren (2010) looks at uncertainty with respect to environmental targets but is unique in studying the quantification of 'eventual impacts of climate change on variability in loads' (p. 470). Gren (2010) also evaluates several climate scenarios and their impact on the total abatement costs of a set of measures but while Lacroix *et al.* (2005) use detailed data for a small agricultural catchment area (145 ha), Gren (2010) evaluates the effect for a large area (30,000 km^2) and includes transport coefficients and the effect of climate change on loads on two types of targets: nutrient reduction and water quality. However, Gren (2010) assumes that the climate effect on loads by individual measures is a modeled average and does not look at the between-year variation for individual crops as this was not the objective of the study. Elofsson (2011) also uses modeled averages for measures but studies the impact of climate change on the cost effective allocation of measures in an even larger area (the Baltic Sea) and uses two different climate scenarios.

Cara *et al.* (2009) look at the impact of climate variability on nitrogen leaching for a specific crop rotation and a focus on one management practice, summer cover crops. The study uses 30 years of annual weather data in a crop-soil model (STICS) to calculate yields (including the effect of disease) and nitrogen leaching under six management systems. The purpose of the study is to compare the long-run economic effectiveness of the eight systems. It only uses the climate data to generate yields for each year in a run for a particular management system and the impact on one crop in the rotation, wheat.

Collentine & Johnsson (2012) describe how a crop permit policy based on expected N leaching for individual crops could lead to cost effective reduction of nitrogen loads to the Baltic Sea. The authors suggest that crop discharge permits be required to cultivate a particular crop. In the paper they propose that permit requirements be based on modeled average leaching using normalized weather for each production area, homogeneous management practices and dominant soil types. The paper concluded that there is a high potential for this type of policy to reduce N loads. However, the effectiveness of the policy is dependent on the modeled leaching to be able to calculate quantitative permit requirements and therefore taking into account the effect of weather on this is important.

CLIMATE VARIATION AND THE COST EFFECTIVENESS OF A CROP PERMIT POLICY

The purpose of the study in this paper is not to compare the cost effectiveness of a crop permit policy with other policy alternatives, as in the studies described above, but to evaluate how annual variability in weather may impact the effectiveness of a crop permit policy based on long-run (20-year) average weather. The effectiveness of a crop permit policy will depend in part on whether crops included in the policy have the same rank with respect to leaching compared to other crops independent of the weather for a particular year.

Under the proposal by Collentine & Johnsson (2012), the permit requirement for each crop is calculated as the difference between the expected leaching for the crop and a baseline for leaching. For example, if policy makers choose a baseline as zero leaching, a farmer growing a particular crop would need to hold sufficient permits to compensate for the total expected leaching of the crop. The choice of a baseline is a political decision; it could be set at any level (for a more detailed description see Collentine & Johnsson (2012)). However, regardless of where the baseline is set, the number of permits will always be based on expected leaching.

A simple example can be illustrated with the data in Table 1. This table reproduces average modeled leaching data for the major crops grown on three dominant soil types in production area 1a in Southern Sweden. Under a zero leaching baseline, a farmer growing potatoes on a sandy loam soil in the area would need to hold discharge permits sufficient to cover an expected load of 61 kg N/ha (Table 1) for each hectare in cultivation. If the same farmer chose to grow oats then she would need to hold permits covering 44 kg N/ha (and for ley 15 kg N/ha) for each hectare in cultivation on the same soil type.

In the policy proposal the load reduction comes from two sources. The price of the permits under the proposal is set at the price for achieving a similar load reduction with another measure (wetlands for example) and permits purchased would be used to finance compensatory measures to achieve the reduction. A second way the policy leads to lower loads is through a redistribution of crops.

The cost of permits changes the relative profitability of individual crops and can affect crop choices and/or field choices. For a farmer that switched growing oats on a field with a sandy loam to a field with sandy clay loam the permit requirement would be 13 kg N/ha lower. For the farmer the costs of permits would be lower because the expected N leaching is lower, i.e. a lower load. This difference in costs would provide an incentive for farmers to change their production choices to minimize costs (maximize profits). However, the leaching coefficients in Table 1 represent

Table 1 | Normalized leaching coefficients (N kg/ha) for Southern Sweden production area 1a by soil and crop type (Johnsson *et al*. 2008)

	Soil type		
Crop type	**Sandy loam**	**Sandy clay loam**	**Clay**
Potatoes	61	43	14
Winter rape seed	55	37	13
Oats	44	31	8
Spring barley	41	29	7
Spring wheat	41	29	11
Rye	38	24	8
Sugar beets	34	22	5
Winter wheat	35	17	6
Fallow	28	19	6
Ley	15	9	3

what the average annual leaching would be if a particular crop was grown over a 20-year period. Unfortunately crop choices are an annual decision and the effectiveness of the policy will depend on the actual weather for the particular year the permits are purchased and the crop grown.

Annual variation in leaching due to weather may or may not have a negative impact on the cost effectiveness of the proposed crop permit policy. It would be expected that leaching would increase during years with higher winter temperatures and more rainfall and be lower during drier, colder years. In Table 2, annual leaching coefficients are reproduced from the SOILNDB program for four major crop types using actual weather for the same production area as in Table 1 (Johnsson *et al.* 2008). The annual variation in leaching as seen in Table 2 can vary greatly for the same crop on each soil type. In Table 2, spring barley varies as much as a factor of five on sandy loam 1991/1995 and sandy clay loam 1991/1996 and to a factor of 10 on clay 1996/1998. However, while this variation due to weather may lead to changes in total loads, if the expected leaching values remain stable relative to each other, a permit policy would still be cost effective.

Each of the crops in Table 1 can be ranked from the highest to the lowest expected leaching for each soil type. For example, the order of the crops on sandy loam in Table 1 follow an order from the one with highest coefficient (potatoes at 61 kg N/ha) to the lowest (ley at 15 kg N/ha). The order is exactly the same for these crops on sandy clay loam but the magnitudes of leaching losses are lower due to the heavier soil type, while on the clay soil the ranking changes somewhat with spring wheat rising in rank above oats and barley. In principle, the stability of these rankings between soil types would ensure that even though a crop permit requirement was based on the wrong soil type (through insufficient information), it would still be relatively efficient, i.e. reduce expected loads compared to crops with higher coefficients grown on the same soil. For example, if permits for oats were mistakenly based on the coefficient for sandy clay loam in Table 1 (31 kg N/ha) but the soil was really sandy loam, then even though the total leaching load is higher than expected (44 kg N/ha) the policy is still effective. If potatoes or winter rape seed had instead been planted on the

Table 2 | Annual leaching coefficients (N kg/ha) for Southern Sweden production area 1a from 1987 to 2003 by soil and crop type (Johnsson *et al.* 2008)

Soil type	Crop type	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
Clay	Spring barley	12.4	3.4	5.9	5.3	15.3	5.3	7.5	8.8	0.8	1.5	6.9	15.8	9.7	3.5	4.8	7.7	5.7
Clay	Winter wheat	10.2	2.6	5.4	4.1	10.1	3.9	5.9	8.2	1.1	1.2	5.4	11.8	6.7	2.9	4.2	6.3	4.5
Clay	Ley 1	1.6	0.6	1.6	0.8	1.5	1.3	2.0	3.0	0.3	0.7	1.9	1.8	1.3	1	0.8	0.8	1.4
Clay	Ley 2 (plowed)	10.7	2.8	6.7	4.5	10.3	6.2	7.6	11.5	0.9	1.8	8.7	14.7	7.8	2.6	3.5	3.2	4.2
Sandy loam	Spring barley	58.0	27.3	41.6	38.9	62.2	39.5	40.6	46.1	12.4	18.3	41.7	60.8	45.4	30.6	38.7	46.3	41.7
Sandy loam	Winter wheat	51.5	23.5	38.0	32.1	46.6	33.5	32.9	43.7	13.7	14.6	34.1	48.8	36.6	29.7	33.5	35.3	33
Sandy loam	Ley 1	12.4	3.0	9.8	5.5	11.6	6.5	9.4	11.6	0.1	1.2	8.1	15.5	10.5	5	5.8	1.9	4.7
Sandy loam	Ley 2 (plowed)	44.1	18.3	34.7	25.5	45.2	32.8	32.7	50.1	6.7	10.3	38.2	51.8	39.5	21.5	22.9	20.4	25.4
Sandy clay loam	Spring barley	43.5	19.7	28.3	28.6	46.8	27.6	29.0	32.0	9.6	9	26.1	49.2	33	20.2	26	31.6	26.2
Sandy clay loam	Winter wheat	28.3	7.6	21.5	16.7	26.4	12.4	15.3	20.6	3.1	4	16.6	28.8	17.4	10.3	15.6	22.3	16.9
Sandy clay loam	Ley 1	6.4	1.7	5.2	1.9	5.5	3.5	5.4	6.7	0.3	0.9	4.4	8.2	4.6	2.2	1.7	1	2.5
Sandy clay loam	Ley 2 (plowed)	31.3	10.9	22.6	15.7	29.6	20.8	22.1	31.2	3.4	5.2	24	38.3	25.9	11.1	12.8	10.3	13.7

field in question then this would have led to increased leaching compared to oats. What this implies is that even though actual leaching for a permit crop may vary from the modeled leaching, if the ranking remains stable a permit policy would still lead to effective abatement, i.e. if expected leaching coefficients are similar when weather varies from year to year.

MATERIALS AND METHODS

The Spearman (rank) correlation is often used in combination or as an alternative to the Pearson correlation for evaluating trends. The Spearman method assesses how well an arbitrary monotonic function is able to describe the relationship between two parameters, without making any assumptions about the frequency distribution of the parameters. The Spearman coefficient (ρ) is calculated from differences in n pairs of raw data (D_i) that have been converted into numerical ranks for each of the series and then evaluated (Equation (1)).

$$\rho = 1 - \frac{6\sum_{i=1}^{n} D_i^2}{n(n^2-1)} \qquad (1)$$

The sign of the coefficient indicates the direction of the relationship. When each of the variables is a perfect monotonic function of the other, a perfect Spearman correlation of +1 or −1 occurs. The annual leaching coefficients in Table 2 are evaluated for this study using the Spearman method.

In Table 2, each year is followed by a modeled leaching coefficient for the 12 crop/soil combinations based on the actual weather recorded for that particular year. For each year these 12 combinations were ranked from the lowest to the highest leaching coefficient and assigned a corresponding numerical value (1 for the lowest, 2 for the second lowest, etc.). If the modeled leaching for more than one of these values was the same, then the average value of the ranking was assigned to these (an example of this can be seen in Table 4). The ranking of each year was then compared pairwise to the ranking of all the other years and the Spearman correlation coefficients calculated as in Equation (1). The result of this is reproduced in Table 3. No comparison was made to the normalized coefficients in Table 1 as these already represent average values for the combinations and any comparison would be redundant.

RESULTS

All of the coefficients in Table 3 are significant at $P = 0.01$. This indicates that there is a high correlation between the rankings of the annual leaching coefficients between all the years studied. A Spearman correlation close to 1 indicates that the degree of leaching (measured in N kg/ha) for each of the four crops holds the same position in the ranking independent of the weather for any particular year. In Table 3 the correlation between the rankings in 1992/1993 is exactly 1; this is because the ranking of the 12 combinations is exactly the same. The rankings for these 2 years are perfect substitutes which can be seen in Table 3 as the correlations for these 2 years and each of the other combination of years is identical.

The lowest Spearman coefficients in Table 3 are found in 1994/1995. To understand what generates a lower Spearman value a detail of the two series for the lowest of these values (0.823 for ley 1 on sandy loam) is reproduced in Table 4. All the leaching coefficients from 1995 were extremely low compared to 1994 (Table 2), as 1995 was a relatively cold and dry year. This may explain why there were a few large shifts in the rankings. Both the two types of ley on sandy loam moved considerably in the ranking as there were almost no leaching losses for the unplowed ley in 1995 and less for the plowed ley as well. The shift in the unplowed ley caused most of the change in the Spearman coefficient for that pair of years. However, even with these shifts, the coefficient was still significant at the 0.01 level, implying that the rankings were similar.

DISCUSSION AND CONCLUSIONS

The effect of weather on leaching is significant. Modeled results reviewed in this paper indicate that annual variation

Table 3 | Spearman rank correlation coefficients (Equation (1)) for annual leaching data from Table 2; pairwise coefficients for all combinations of years from 1987 to 2003

	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
1987	0.991	0.988	0.984	0.977	0.988	0.988	0.967	0.864	0.970	0.970	0.977	0.911	0.991	0.977	0.928	0.977
1988		0.972	0.986	0.993	0.972	0.972	0.937	0.879	0.967	0.951	0.972	0.972	0.979	0.979	0.951	0.986
1989			0.979	0.958	1.000	1.000	0.979	0.858	0.970	0.986	0.958	0.986	0.979	0.965	0.902	0.951
1990				0.979	0.979	0.979	0.944	0.851	0.949	0.951	0.958	0.972	0.979	0.993	0.944	0.986
1991					0.958	0.958	0.930	0.865	0.953	0.944	0.979	0.965	0.965	0.972	0.944	0.979
1992						1.000	0.979	0.858	0.970	0.986	0.958	0.986	0.979	0.965	0.902	0.951
1993							0.979	0.858	0.970	0.986	0.958	0.986	0.979	0.965	0.902	0.951
1994								0.823	0.949	0.986	0.965	0.986	0.958	0.930	0.853	0.916
1995									0.927	0.865	0.837	0.830	0.858	0.858	0.928	0.879
1996										0.981	0.953	0.956	0.946	0.932	0.939	0.942
1997											0.965	0.979	0.951	0.930	0.888	0.923
1998												0.986	0.965	0.951	0.909	0.958
1999													0.986	0.965	0.895	0.958
2000														0.986	0.923	0.979
2001															0.951	0.993
2002																0.972

Table 4 | Ranking data for the lowest pairwise Spearman coefficient in Table 3 (1994 and1995)[a]

Soil type	Crop	Rank 1994	Rank 1995	Difference between rankings (*d*)	d^2
Clay	Spring barley	4	4	0	0
Clay	Winter wheat	3	6	−3	9
Clay	Ley 1	1	2.5	−1.5	2.25
Clay	Ley 2 (plowed)	5	5	0	0
Sandy loam	Spring barley	11	11	0	0
Sandy loam	Winter wheat	10	12	−2	4
Sandy loam	Ley 1	6	1	5	25
Sandy loam	Ley 2 (plowed)	12	9	3	9
Sandy clay loam	Spring barley	9	10	−1	1
Sandy clay loam	Winter wheat	7	7	0	0
Sandy clay loam	Ley 1	2	2.5	−0.5	0.25
Sandy clay loam	Ley 2 (plowed)	8	8	0	0
				$\sum d^2$	50.5
				$6\sum d^2$	303

[a]Based on the leaching coefficients in Table 2.

in nitrogen leaching can be as high as a factor of 10 depending on the weather for a particular year. These results are based on 20 years of historic weather data. The historic data used include years with high and low annual precipitation and temperatures. Climate change is expected to lead to even greater variation and values that lie outside the range of the historic data. The effectiveness of abatement policies will be impacted by how well this variation is accounted for when the policy is designed and evaluated.

The crop permit policy analyzed by Collentine & Johnsson (2012), which would set a fee for growing crops based on average expected leaching, is cost effective because it places a higher cost on crops which have a greater negative impact on the environment, i.e. higher leaching losses. The higher cost for crops which leach more brings about nitrogen reductions in the short run using the fees paid to finance compensatory abatement measures. However, in the long run higher costs would lead to lower nitrogen losses due to crop redistribution. Since this long-run effect arises due to the relative ranking of crops on soil types, it is important for efficiency that the signal given by modeled ranking is the same for average and annual weather.

The results presented in Table 3 indicate that the rankings of the annual weather leaching coefficients are similar for the four crops and three soil types in the study. This in turn means that if ranking is used for determining leaching losses, then regardless of whether average (normalized) or annual weather were used the ranking of losses would be similar. Although total nitrogen losses would vary depending on the impact of actual weather on the crop grown, the relative efficiency of the crop permit policy evaluated in this paper would be the same for both types of weather. The long-run cost signals from permit fees and the impact on cropping decisions would lead to decisions that were cost effective in reducing nitrogen losses. While these conclusions are only valid for a limited number of crops (four) on a limited number of soil types (three) in one production area in Southern Sweden, the analytical method applied in this paper is useful for making comparisons.

While the analysis presented in this paper provides support for the use of a crop permit policy based on expected leaching, there needs to be further studies that expand the number of crops, soil types and weather analyzed before conclusions may be made. Determining the stability of modeled leaching losses is not only of use for the crop permit policy discussed but for any abatement policy which uses modeled losses for differentiating between alternatives. For example, emission trading programs that include agricultural sources have been proposed that would allow trades to be made based on modeled losses (Collentine 2006; Wainger & King 2007; Selman *et al*. 2009). The effectiveness of these latter types of program will also be affected by variation in weather, soil type or management practice. Using the Spearman method is one way to assess *ex ante* whether the impact on leaching of the variables analyzed is sufficiently similar and the policy effective even when there is annual variation in weather and an impact from climate change.

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REFERENCES

Cara, S., Jacquet, F., Reynaud, A., Goulevant, G., Jeuffroy, M.-H., Lucas, P. & Montfort, F. 2009 Economic Analysis of Summer Fallow Management to reduce Take-All and N-Leaching in a Wheat Crop Rotation. Toulouse School of Economics Working Paper Series, pp. 09–043.

Collentine, D. 2006 Composite market design for a Transferable Discharge Permit (TDP) system. *J. Environ. Plan. Manage.* **49** (6), 929–946.

Collentine, D. & Johnsson, H. 2012 Crop discharge permits for reduction of nitrogen loads to the Baltic Sea. *JAWRA J. Am. Water Resour. Assoc.* **48** (1), 24–31.

Elofsson, K. 2011 Contracting Nitrogen Abatement in the Baltic Proper Watershed Under the Risk of Climate Change. Paper presentation at the EAAE 2011 Congress Zurich, Switzerland, 2011.

European Court of Auditors 2011 Is Agri-environment Support Well Designed and Managed? Special Report No 7, European Court of Auditors, Luxembourg.

Gren, I-M. 2010 Climate change and the Water Framework Directive: cost effectiveness and policy design for water management in the Swedish Mälar region. *Clim. Change* **100**, 463–484.

Johnsson, H., Larsson, M., Lindsjö, A., Mårtensson, K., Perssson, K. & Torstensson, G. 2008 *Nutrient Leaching from Arable Land in Sweden. Calculations of the Normalized Loads of Nitrogen and Phosphorus for 1995 and 2005 (Swedish title: Läckage av näringsämnen från svensk åkermark – Beräkningar av normalläckage av kväve och fosfor för 1995 och 2005)*. Swedish Environmental Protection Agency, Stockholm, Sweden, 228 pp.

Lacroix, A., Beaudoin, N. & Makowski, D. 2005 Agricultural water nonpoint pollution control under uncertainty and climate variability. *Ecol. Econ.* **53** (1), 115–127.

Meier, H. E. M. 2006 Baltic Sea climate in the late twenty-first century: a dynamical downscaling approach using two global models and two emission scenarios. *Clim. Dyn.* **27** (1), 39–68.

Meier, H. E. M., Hordoir, R., Andersson, H. C., Dieterich, C., Eilola, K., Gustafsson, B. G., Höglund, A. & Schimanke, S. 2012 Modeling the combined impact of changing climate and changing nutrient loads on the Baltic Sea environment in an ensemble of transient simulations for 1961–2099. *Clim. Dyn.* **39** (9–10), 2421–2441.

Selman, M., Sprague, E., Walker, S. & Kittler, B. 2009 *Nutrient Trading in the Chesapeake Bay Region: An Analysis of Supply and Demand*. Pinchot Institute for Conservation, Washington, DC.

Shortle, J., Ribaudo, M., Horan, R. & Blandford, D. 2012 Reforming agricultural nonpoint pollution policy in an increasingly budget-constrained environment. *Environ. Sci. Technol.* **46** (3), 1316–1325.

SNV, Swedish Environmental Protection Agency 2008 Sweden's commitment in the Baltic Sea Action Plan (Swedish title: Sveriges åtaganden i Baltic Sea Action Plan). Report 5830, Swedish Environmental Protection Agency, May 2008.

Wainger, L. & King, D. 2007 Establishing Trading Ratios for Point – Non-Point Source Water Quality Trades. University of Maryland Center for Environmental Science Technical Report No. TS-523-07.

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