Improving the cost-effectiveness of water quality improvements through spatial scale changes to target-setting

Mikołaj Czajkowski, Hans E. Andersen, Gite Blicher-Mathiasen, Wiktor Budziński,
Katarina Elofsson, Jan Hagemejer, Berit Hasler, Christoph Humborg, Jim Smart,
Erik Smedberg, Per Stålnacke, Hans Thodsen, Adam Wąs, Maciej Wilamowski,
Tomasz Żylicz, Nick Hanley

Aim of the study

- Ambitious targets to reduce nutrient loadings to the Baltic Sea
- A policy, which sets a target reduction at the largest area of spatial aggregation (the entire Baltic Sea) is more cost-effective than a policy, which imposes targets at lower levels of spatial disaggregation (e.g., sea basins, countries, watersheds, farms)
  - Potential to take advantage of options in areas where loading reductions from agriculture into the Baltic can be achieved at a relatively low cost (*hot-spots*)
  - Large spatial variations of the marginal “abatement” costs for reducing N loadings entering the Baltic Sea
    - The efficiency (profitability) of using mineral fertilizers / manure (livestock herds)
    - The relationship between N fertilizer/ manure use and N concentrations in the root zone
    - The extent and speed with which N in the root zone is transported to the Baltic as increased loading
- How much more effective are larger area targets?
- Where are the cost-effectiveness hot-spots located?

Our model = bottom up approach linking agricultural profits, changes in root zone N concentrations and transport to the Baltic Sea

- 19,023 10x10 km grid cells
  - 117 watersheds
  - 10 countries
  - 14 sea basins
- 11 crop types + 3 livestock types
- Grid-cell specific root-zone N leaching
  - Modelled using DAISY – a separate soil-vegetation-atmosphere model (Abrahamsen and Hansen, 2000; Andersen et al., 2016)
- Grid-cell specific retention
  - Surface water nitrogen retention (117 watersheds) provided by the MESAW model (Grimvall and StÅLnacke, 1996)
  - Groundwater retention (each grid cell) estimated as the difference between cumulated watershed rootzone nitrogen leaching and the total riverine nitrogen loss from the watershed corrected for surface water retention (Andersen et al., 2016)
- Grid-cell specific profit functions
  - Experimental yield functions (Pedersen, 2009) adapted to all the grid cells by applying a horizontal-scaling calibration procedure (c.f. Brady, 2003)
  - Livestock profitability calculated using the Standard Gross Margin approach (weighted average for each of the NUTS 2 regions based on FADN (SGM for all animals groups) and Eurostat data (structure of the heard), averaged over 3 successive years for each region (to smooth out temporal fluctuations)
- Grid-cell specific data on natural and economic conditions and current agricultural practices

Previous studies

Study	No. of measures	No. of target regions	No. of target levels	Cost function	Leaching function, data
Gren, Jannke and Elofsson (1997)	5	14	8	nonlinear	linear, various sources
Ollikainen and Honkatukia (2001)	-	9	1	quadratic	----
Schou et al. (2006)	5	24	1	quadratic	linear, PLC-4 HELCOM data
COWI (2007)	9	24	1	linear	linear, based on distance
Gren (2008)	9	24	6	nonlinear	linear, PLC-4 HELCOM data
Wulff et al. (2014)	5	22	1	nonlinear	nonlinear, high resolution (117 watersheds) DAISY model
Ahlvik et al. (2014)	10	23	1	nonlinear	nonlinear coupled with marine model
Our approach	11 x 2	19,023	5 x 10	nonlinear	non-linear, high resolution (19,023 grid cells), DAISY model with grid-level combined groundwater and surface water retention

The optimization problem

$$\min \sum_{r=1}^{R} \sum_{g_r=1}^{G_r} TC_{g_r}\left(\Delta N\_fert_{c,g_r}, \Delta N\_man_{c,g_r}\right) \quad \text{s.t.} \quad \begin{cases} \forall_{r=1..R} \sum_{g_r=1}^{G_r} \left(1-q_{g_r}\right) N\_leach_{g_r}\left(N\_fert^{*}_{c,g_r}, N\_man^{*}_{c,g_r}\right) \geq T_r \\ \forall_{g=1..G} \ \forall_{c=1..11} \ 0 \leq N\_fert^{*}_{c,g} \leq N\_fert^{0}_{c,g} \\ \forall_{g=1..G} \ \forall_{c=1..11} \ 0 \leq N\_man^{*}_{c,g} \leq N\_man^{0}_{c,g} \end{cases}$$

where

$$\begin{aligned} TC_g\left(\Delta N\_fert_{c,g}, \Delta N\_man_{c,g}\right) = & \sum_{c=1}^{11}\left(ha_{c,g}\left(p_{c,g} Y_{c,g}\left(\Delta N\_fert_{c,g} + \Delta N\_man_{c,g}\right) - p_{f,g} \Delta N\_fert_{c,g}\right)\right) - \\ & sgm_{cattle,g} \Delta L_{cattle,g} - sgm_{pigs,g} \Delta L_{pigs,g} - sgm_{poultry,g} \Delta L_{poultry,g} \, p_{c,g} \end{aligned}$$

$$Y_{c,g}\left(N\_frt_{c,g}, N\_man_{c,g}\right) = \alpha^{0}_{c,g} + \alpha^{1}_{c,g}\left(N\_frt_{c,g} + N\_man_{c,g}\right) + \alpha^{2}_{c,g}\left(N\_frt_{c,g} + N\_man_{c,g}\right)^{2}$$

$$N\_man_{c,g} = \gamma_{c,cattle,g} L_{cattle,g} + \gamma_{c,\mathrm{pigs},g} L_{pigs,g} + \gamma_{c,poultry,g} L_{poultry,g}$$

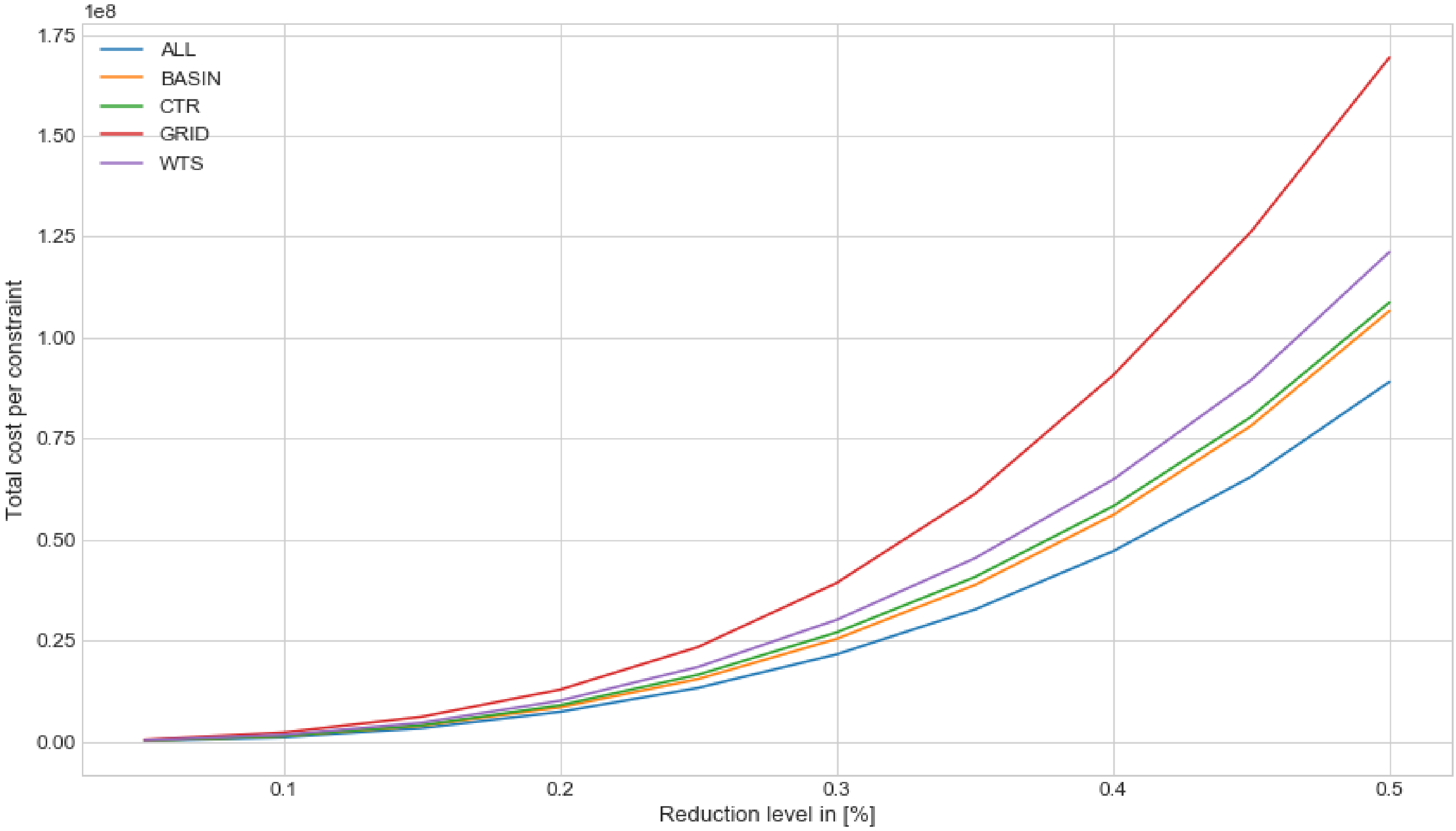
$$N\_leach_g\left(N\_fert_{c,g}, N\_man_{c,g}\right) = \sum_{c=1}^{11}\left(ha_{c,g}\left(\beta^{0} \exp\left(\beta^{1}_{c,m} + \beta^{2}_{c,m} clay_g + \beta^{3}_{c} carbon_g + \beta^{4}_{c,m} \log\left(N\_input_{c,g}\right)\right)\right)\right)$$

$$N\_input_{c,g} = N\_fert_{c,g} + N\_man_{c,g} + N\_fix_{c,g} + N\_seed_{c,g} + N\_dep_g$$

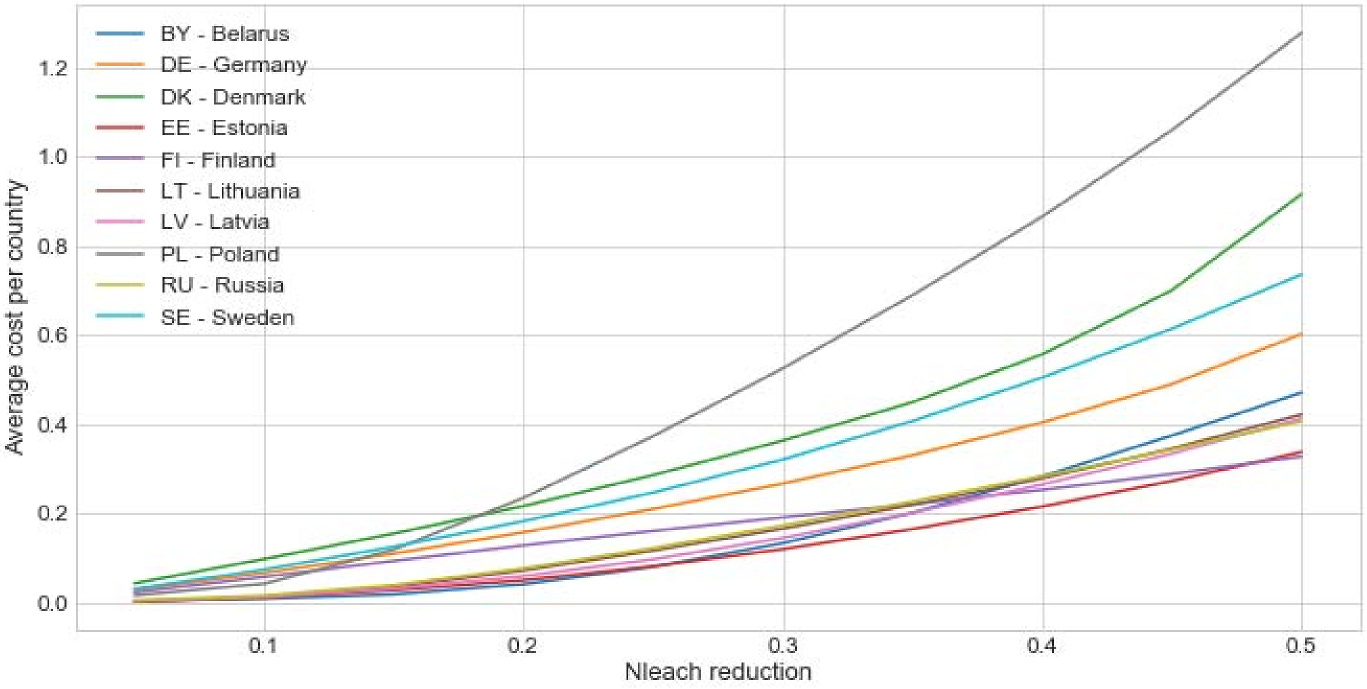
Scenarios compared

- Targets corresponding to relative reductions of 5%, 10%, … , 50% (of what is theoretically possible to reduce) allocated to:
  - The entire Baltic Sea (ALL)
  - 14 sea basins (BASIN)
  - 10 countries (CTR)
  - 117 watersheds (WTS)
  - 19,023 grid cells (GRID)

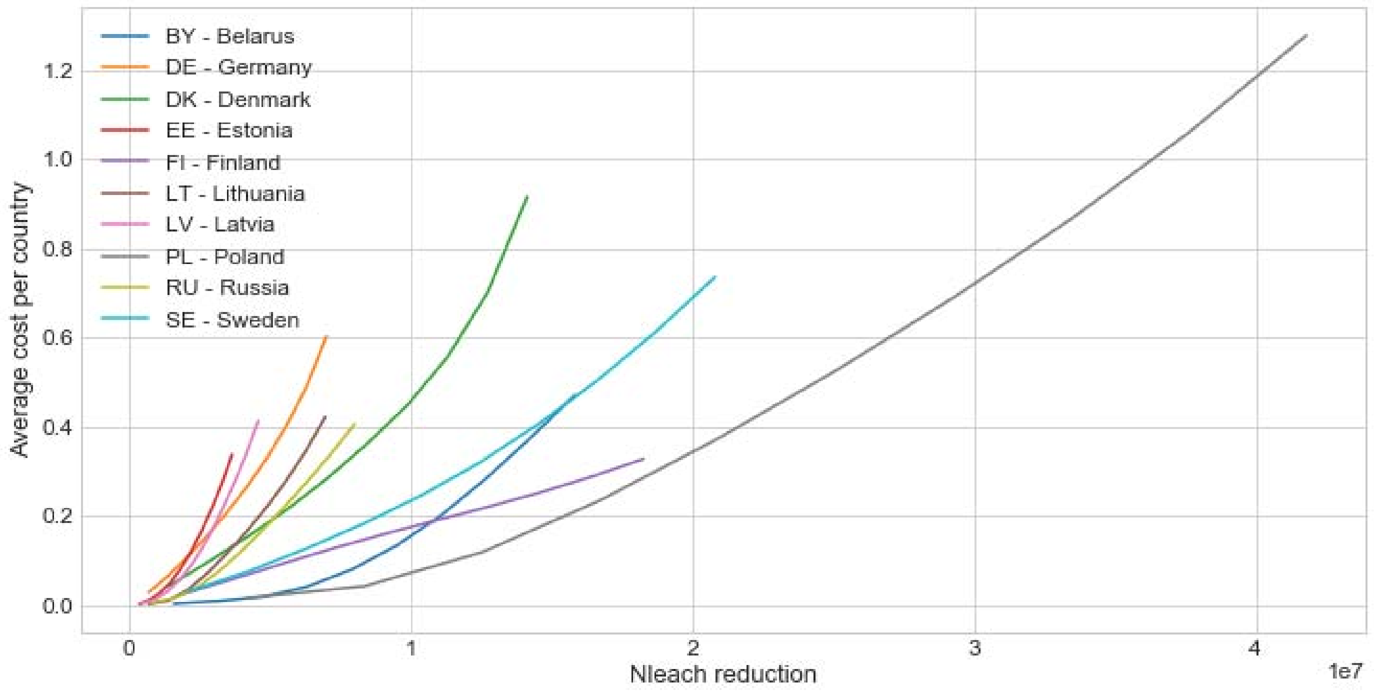
Total cost of reaching a given reduction target for various allocations of targets



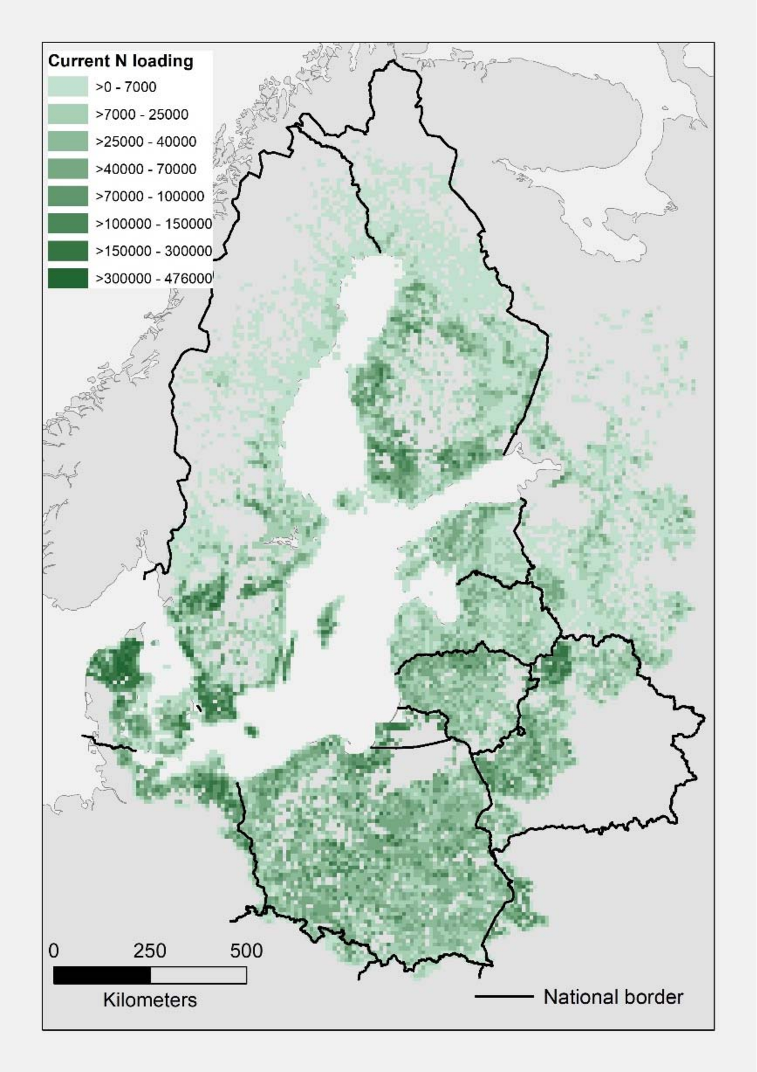
Average cost of **relative** reductions in various countries (targets allocated to countries)

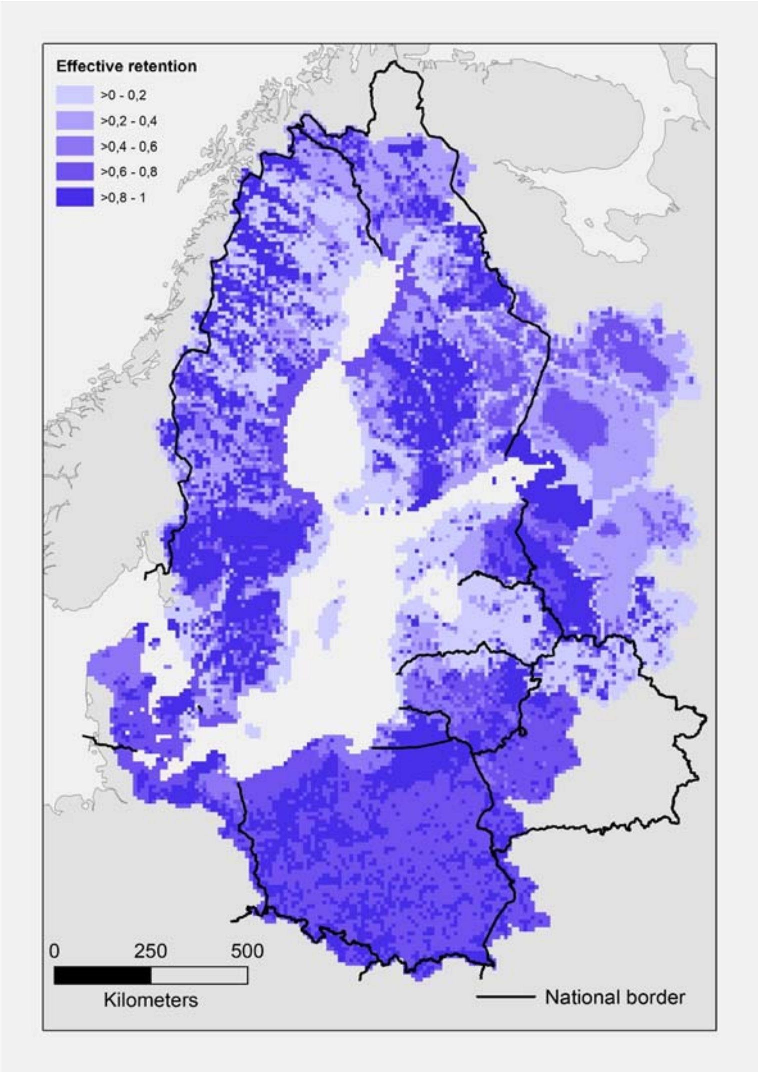


Average cost of **absolute** reductions in various countries (targets allocated to countries)

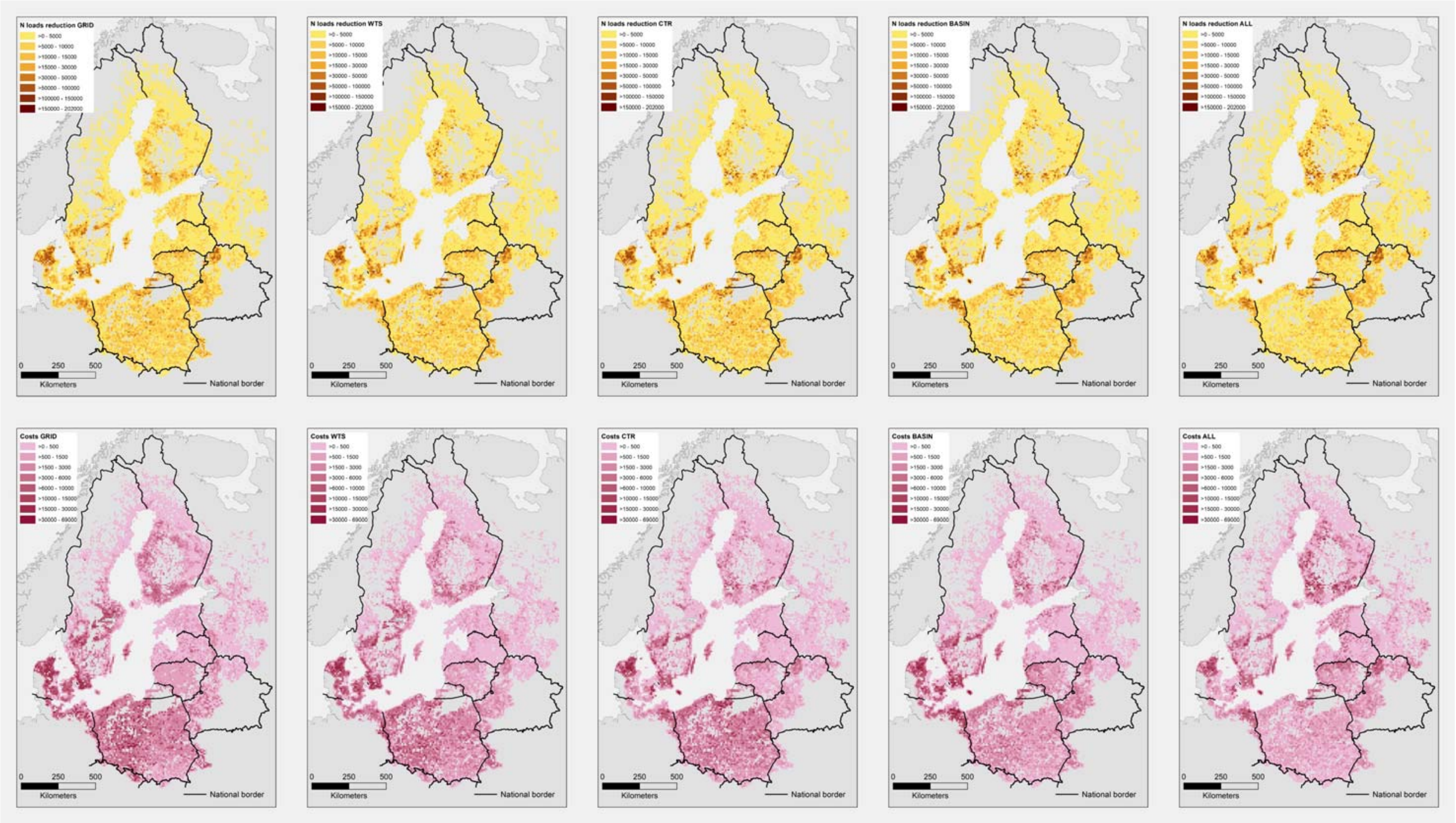


Current N loadings and retention

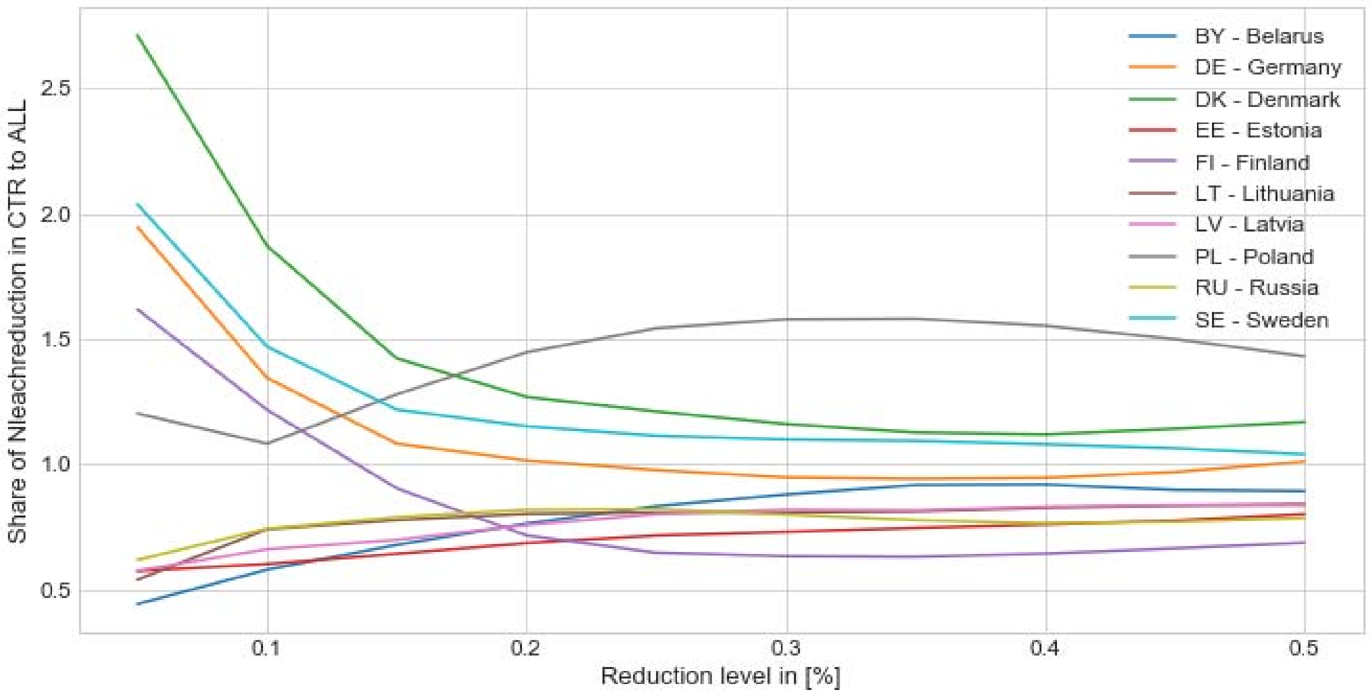




N loadings reductions (25%) and the associated costs under various target allocations



Relative differences between countries' reductions
N reductions in CTR allocations / N reduction in ALL allocations



Conclusions

- The first model to use such detailed resolution level
- New (arguably better) estimates of the N reductions cost functions
- Demonstrate the extent of the economic benefits of policies targeting larger geographical scales
  - May require international cooperation, compensations etc.
- Identify efficiency hot-spots, which should be targeted first
  - May require using location-specific measures and incentives
- Given mixing of the BS waters, the HELCOM targets for basins are likely not efficient, as they were not based on economic analysis
- Limitations: N only, no other measures included (diffuse or point-source), ignoring side benefits (e.g., improvements in lakes and rivers along the way) etc.

Thank you

- Contact me
  - mc@uw.edu.pl
  - czaj.org

- Acknowledgements
  - The work presented is part of the BONUS GO4BALTIC project: http://projects.au.dk/go4baltic/
  - The BONUS GO4BALTIC project is supported by BONUS (Art 185), funded jointly by the EU and national funding institutions in Denmark (the Innovation Fund), Estonia (Estonian Research Council ETAG), Finland (Academy of Finland), Poland (NCBR) and Sweden (FORMAS)