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Effect of European post-Kyoto Climate Policies on Nordic Air Quality

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Sammendrag:. Strengere forpliktelser for utslipp av klimagasser etter 2012 vil bidra til reduserte utslipp av luftforurensninger i de nordiske landene, reduserte kostnader til tekniske tiltak og gevinster i form av mindre forsuring, eutrofiering, ozoneffekter på vegetasjon og helseeffekter av partikler. Imidlertid er reduksjonene i utslipp mindre i de nordiske landene enn i andre deler av Europa på grunn av forventet bruk av fleksible mekanismer (slik som kvotehandel) som vil innebære at reduksjoner i utslipp skjer andre steder og spesielt i Russland og Øst-Europa. På den annen side vil de nordiske landene ha miljøgevinster av reduksjoner i utslipp i andre regioner. Flere sektorer inkludert i det europeiske klimakvotesystemet vil innebære små økte utslipp av luftforurensninger. Dersom EU og Norge er involvert i et klimasamarbeid som ikke inkluderer andre regioner vil det innebære større utslippsreduksjoner av klimagasser, og dermed også luftforurensninger i de nordiske landene. Dette vil ha gevinster for økosystemene i den sørlige delen av Skandinavia, men vil føre til økt forsuring i nord på grunn av høyere utslipp i Russland. Veitrafikk er særlig viktig for eksponering for partikkel-forurensning og denne kilden er mindre påvirket av de ulike opsjonene for klimapolitikk. Så lenge internasjonale klimaforpliktelser etter 2012 er uavklart vil det derfor være knyttet usikkerhet til til nødvendige kostnader for å nå mål for utslipp av luftforurensninger, effekter på økosystemer og eksponering for partikkelforurensning i 2020. Mye av denne usikkerheten er knyttet til deltagelse av Russland og Øst-Europa.

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Abstract: Stricter commitments for GHG emissions in the post-Kyoto period will contribute to reduced emissions of air pollutants in the Nordic countries, avoided costs for end-of-pipe abatement to reach a specific target, and benefits for ecosystems and human health. However, reductions in emissions in the Nordic countries are smaller than in other regions since use of the flexible mechanisms implies a shift in GHG abatement, and co-benefits, to other regions – in particular Russia and Eastern Europe. On the other hand, the Nordic countries benefit from reductions in emissions in other regions. Expanding the number of sectors included in the emission trading scheme will imply increased air pollutant emissions and less benefits to ecosystems. If EU and Norway are involved in a climate policy cooperation not involving other regions, this will imply that more greenhouse gas emission reductions are undertaken in the Nordic countries with subsequent reductions in air pollutant emissions. This would benefit ecosystems in southern Scandinavia, but acidification would increase in the north because of increased emissions in Russia. For human exposure to $PM_{2.5}$, road transport is particularly important and this source is less influenced by the options for climate policies. Therefore, as long as post-Kyoto climate policies are unknown, there are large uncertainties about the required costs to achieve different level of air pollutant emissions, ecosystem protection and human exposure in 2020. A large part of this uncertainty comes from the degree of Russian and Eastern Europe climate policy cooperation.

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1 Introduction

Options for mitigating air pollution have traditionally been directed at technical end-of pipe measures. On the other hand, strategies to reduce emissions of greenhouse gases often are focused on changes in the energy system and apply policy instruments such as taxes and emission trading. The changes in the energy system resulting from climate policies will also change emissions of air pollutants (Syri et al., 2001; Van Vuuren et al., 2006; EEA, 2006).

Until 2012 there is a cap on greenhouse gas (GHG) emissions in Europe and some industrialised countries outside Europe due to the commitment of the EU member states and other countries under the Kyoto Protocol. The Kyoto Protocols opens up for emission trading, which implies that emission reductions can be undertaken where costs are the lowest. This would also often imply that emissions of air quality pollutants like sulphur dioxide (SO_2) and nitrogen oxide (NO_x), would be more strongly reduced where CO_2 abatement is cheapest (and less in other regions) and not where the impact of emissions is largest. The climate policies after 2012 are unsettled and will probably remain so for several years.

In parallel with discussions on future climate policies under the United Nation Framework Convention on Climate Change, the Gothenburg Protocol of the Convention on Long Range Transboundary Air Pollution is under review and revised ceilings for emissions of various air pollutants are being considered. Similarly, the National Emission Ceiling Directive (NEC) of the European Union is under revision. Clearly, uncertainties about future climate policies globally and in the European Union adds uncertainties to the costs required to reduce air pollutant emissions and therefore to the optimalisation of ceilings under the Gothenburg Protocol and NEC.

The goal of this project is to analyze how various European post-2012 strategies to reduce greenhouse gas emissions (specifically the cap on emissions, emission trading and taxes) will influence air pollution in the Nordic countries in particular, but also in the rest of the EU and Europe. The strategies will be evaluated in the light of i) the alternative (or avoided costs) of air pollutant abatement, ii) welfare effects of CO_2 reductions (changes in the energy system) and iii) physical damage to ecosystems. In the analysis we are using available models in the Nordic countries (the GRACE general equilibrium model at CICERO and the RAINS model operated in Denmark). To illustrate the case of particulate matter exposure, a national population exposure model is used for Finland.

We briefly present the approach, tools, and scenarios in Chapter 2, the results in Chapter 3 and a discussion and conclusion in Chapters 4 and 5.

2 Overview of tools and methodologies

Energy and CO_2 emission scenarios were generated until 2020 using the general equilibrium model GRACE under a range of assumptions about GHG emission caps, GHG emission trading and carbon taxes in Europe (see Section 2.4). The energy consumption from GRACE was transferred to the RAINS model activities. Because the aggregation levels are very different in the two models, the transfer of data requires particular consideration (Section 2.3). The RAINS model was used to generate emissions of SO_2, NO_x and particulate matter ($PM_{2.5}$) and to calculate the effects on the environment (eutrophication, acidification, ozone effects on crop, and human exposure to particulate matter).

2.1 *The GRACE model*

The CICERO GRACE model (Aaheim and Rive, 2005) is used to generate the alternative climate policy scenarios, providing economic and energy data for the RAINS model. It is also used to estimate associated CO_2 emissions. GRACE is a recursive multi-sector, multi-region computable general equilibrium (CGE) model, which includes energy and CO_2 emissions accounting. In this project, the model is run for the period 2000-2020, in 5-year steps. Economic and energy efficiency growth assumptions are taken from the SRES B2 (mid-growth) scenario (IPCC, 2001). The GRACE model is flexible with regards to sector and regional inclusion. In this project, the model includes 14 regions and 24 sectors (see Table 1).[1]

Table 1. Regions and sectors included in GRACE

Regions	**Sectors**
DEN Denmark	GAS Natural gas works
SWE Sweden	ELY Electricity and heat
NOR Norway	OIL Refined oil products (i.e. gasoline)
FIN Finland	COL Coal products
UKI United Kingdom and Ireland	CRU Crude oil
GER Germany	I_S Iron and steel industry
FRA France and Switzerland	CRP Chemical industry
POL Poland	NFM Non-ferrous metals (aluminium)
BAL Lithuania, Latvia, and Estonia	NMM Non-metallic minerals (glass, concrete)
MED Iberia, Italy, and Greece	TRN Transport equipment
REU Rest of EU (including accession states)	OME Other machinery
REE Rest of Eastern Europe	OMN Mining
RUS Russian Federation	FPR Food products
ROW Rest of the world	PPP Paper-pulp-print
	LUM Wood and wood-products
	CNS Construction
	TWL Textiles, wearing apparel, and leather
	OMF Other manufacturing
	AGR Agricultural products
	T_T Transport
	ATP Air Transport
	SER Commercial and public services
	DWE Dwellings

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[1] It should be noted that the “Norway” region in GRACE at present includes Liechtenstein and Iceland, as is featured in the originating GTAP database. Given the relative sizes of these three economies, however, we suggest it acceptable to refer to (and interpret) the region as “Norway” for the purposes of our analysis.

The GRACE model is calibrated around the GTAP v5.4 database (Dimaranan and McDougall, 2002), which is a large, comprehensive, and internally consistent social accounting matrix of the global economy. CO_2 emission data are taken from the GTAP/EPA database (Lee, 2002), and energy demand data and structure from the GTAP-EG model (Rutherford and Paltsev, 2000). Production is modelled through nested constant elasticity of substitution (CES) functions, detailed in Aaheim and Rive (2005). Substitution elasticities between inputs such as energy, non-energy goods, capital, labour, and natural resources are taken from the updated EPPA 4 model at Massachusetts Institute of Technology (Paltsev et al., 2005).

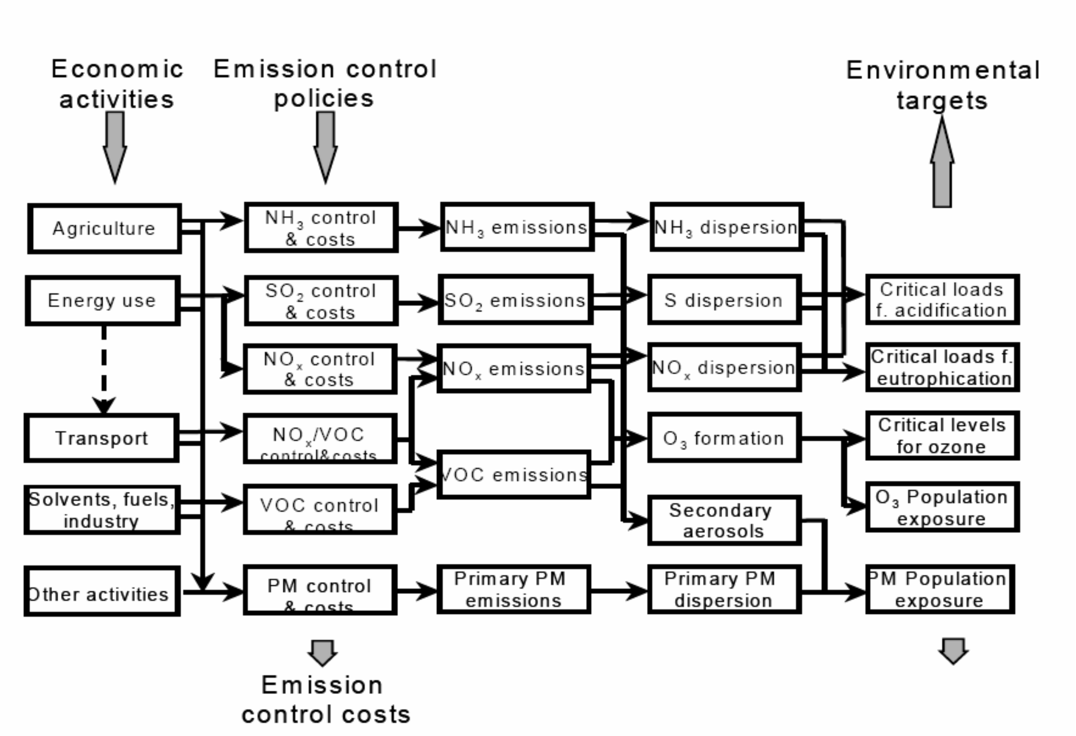
In this study, climate change policy is modelled in GRACE through annual emissions allowances (emission caps) to participating regions, and an emissions trading scheme (ETS). GRACE is flexible with regards to which regions and sectors participate in climate policy; these are adjusted as a part of our scenario analysis and comparison (see Section 2.4). CO_2 emissions are modelled as a fixed factor (Leontief technology) input to sector and household level energy demand, and carbon abatement is undertaken through substitution away from carbon-intense energy inputs. There are no explicit abatement costs in GRACE; the cost of an emission permit (in the tradable permit market) is calculated endogenously as the opportunity cost of energy input substitution. It is also possible to implement a tax on CO_2 emissions in GRACE, with flexibility on the regional and sectoral burden of this tax. In our scenarios, the Kyoto Protocol (KP) is undertaken in 2010 with emissions trading among the European Parties that have emission reduction obligations. In our scenarios (Section 3), alternative assumptions are made with regards to post-Kyoto CO_2 abatement levels, taxes, and emissions trading.

2.2 The RAINS model

The Regional Air Pollution Information and Simulation (RAINS) model has been developed by the International Institute for Applied Systems Analysis (IIASA) (Amann et al., 2004). The model has evolved over a period of more than 20 years, as a result of attempts by the international community to base policy decisions on scientific knowledge. The present model – and the way it is used – is a product of the various research and policy initiatives taken during this period. One of its main purposes during the last 10-15 years has been to assist policy development on transboundary air pollution in Europe. The model has been used to assist the negotiations of the second sulphur protocol and the Gothenburg Protocol under the Convention on Long-range Transboundary Air Pollution (CLRTAP) and for the NEC Directive.

The RAINS model combines information on economic and energy development, emission control potentials and costs, atmospheric dispersion characteristics and environmental sensitivities towards air pollution. The model addresses threats to human health posed by fine particulates and ground-level ozone, as well as risk of ecosystems damage from acidification, excess nitrogen deposition (eutrophication) and exposure to elevated ambient levels of ozone. The model can be used for scenario analysis. Given future energy consumption, the model calculates the resulting emissions, resulting depositions, costs of selected control strategies, and the resulting critical loads exceedances and impacts on human health. Furthermore, the model can be used in an optimalisation mode. On the basis of defined deposition targets, energy and agricultural scenarios, the required geographical distributed abatement measures can be calculated. The RAINS model consists of five main elements: 1) scenarios for energy and agriculture, 2) emission inventories and projections, 3) pollution transport matrices, 4) critical loads and 5) abatement costs. The structure of the model is illustrated in figure 1.

Figure 1. Structure of the RAINS model (http://www.iiasa.ac.at/rains/review)



2.3 *Transfer of data between GRACE and RAINS*

As earlier described in this report, the RAINS model requires scenario estimations on expected energy and pollutant relevant activities in Europe, and how they progress over time, in order to calculate the resulting emissions of SO_2, NO_x and $PM_{2.5}$. These scenarios are typically given by the energy model PRIMES (Capros and Mantzos, 1999) and the transport model TREMOVE (De Ceuster et al., 2005). In this study, however, we rather use the GRACE model to provide the time-series activity level input to the RAINS model. Developing a method for transferring output data from the GRACE model to a form that was useful and effective for input to RAINS proved to be a challenging task. Not only must the input data capture the key energy and activity differences between our alternative scenarios, they must also be provided in a format that can be put into the RAINS model.

A number of practical constraints exist when replacing the PRIMES and TREMOVE models with the GRACE model as inputs into the RAINS model. Three major constraints are:

1. GRACE is a top-down model, and presents sectors and activities in a more aggregated manner than PRIMES, TREMOVE, and RAINS.
2. GRACE represents activities and outputs in US dollar ($) values (as with all CGE models), rather than physical units (such as PJ, km, etc.), which are required to run the analyses in RAINS.
3. Being a top-down model, the representation of specific energy and process technologies – and technological change between them – is non-existent in GRACE.

Developing a transfer system between GRACE and RAINS required that these obstacles be overcome. The first constraint – the aggregation – is overcome by developing a mapping system between the aggregated GRACE sectors, and the detailed RAINS sectors. RAINS activities are mapped to a particular GRACE sector, and during the conversion of GRACE to RAINS format, progression of each RAINS activity will depend on the progression of the GRACE sector it is mapped to. The GRACE sectors are classified according to the GTAP database as described by Huff et al. (2000). The information on RAINS sector and activity classification is supplied by the web page (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/). The RAINS classification is consistent with (can be translated to) SNAP (Selected Nomenclature for Sources of Air Pollution) and NFR (Nomenclature for Reporting) classifications. Generally speaking, mappings were performed using these classifications; others simply required judgement of best fit. The mappings are displayed in Annex Table A1.

The second constraint is driven by the representation of activity levels and output quantities in GRACE in dollar value terms, rather than physical units. RAINS requires physical units (PJ, km, population) as inputs. As such, while the relative growth of activity levels in each sector and country over time can reliably taken from GRACE, a fixed physical unit starting point is required so that the data can be entered into the RAINS model. Our GRACE scenarios are represented over the period 2000-2020, and thus the starting point is taken in 2000. We have taken the initial activity level values (in physical units) from the RAINS Online activity level database (CP_CLE scenario (climate policy)) for each country. The growth (or decrease) of these activity levels beyond 2000 is then calculated from the relative growth (or decrease) in the activity levels from the GRACE model. This way, the impacts of alternative climate policies is captured by our RAINS inputs. This is illustrated in Annex Equation A1 in Section 7.1.

The final constraint is related to the representation of specific technologies and technological change in PRIMES, TREMOVE and RAINS, which does not feature in the GRACE model. Being a top-down model, GRACE only represents aggregated versions of each sector, and does not feature specific technological changes within each sector. Differences between each technology can be important for air quality, and the technologies may change significantly over time – including in the 20 years that each of our scenarios span. Because the GRACE model represents only aggregate sector activity, we employ an exogenous technological change adjustment step between the GRACE output data and their input into RAINS to capture these changes. This step, it should be noted, is the same across all our scenarios and thus should not be considered to be a true representation of bottom-up induced technological change. Because the adjustments are the same for each scenario, the relative emissions levels are not affected. Modelling endogenous technical change at a detailed level would not have been possible with the resources available in this project.

The step involves obtaining activity levels for each region (for the model period 2000-2020) from a reference RAINS scenario. We use the CP_CLE scenario from the RAINS Online database. Each of the activity levels (in time series format) are then grouped into categories based on the GRACE sectors they are mapped to – for example, transport, or coal use in boilers. Each category would include technologies that existed in 2000, as well as new technologies that are introduced over time, and those that are phased out over time. For each time period (2005, 2010, 2015, 2020), we record the activity level share that each activity makes up within its category. We then assume that for each year and region, these technology shares are constant across all our scenarios. The absolute level of each activity in the RAINS input, then, is dependent on (a) the initial fixed starting point in 2000, (b) the growth index of the associated GRACE sector, and (c) the technological share adjustment. This is further outlined in Annex 1, Section 7.2.

Our data transfer system between GRACE and RAINS has a number of limitations, as we have outlined here. The GRACE model may not be the first best option for providing activity level input to the RAINS model, owing to its lack of technological detail. However, it offers a key advantage over PRIMES in its flexibility that captures the wider output and price impacts that would cascade across all regions and sectors as a result of the different climate policies. This is particularly important when analysing emissions trading systems.

2.4 The scenarios

We generate a set of six alternative climate policy scenarios, plus one “no climate policy” scenario, in the GRACE model. The scenarios are built on a variety of assumptions about specific policy options. By changing these specific assumptions between scenarios, we can determine their respective impacts on air quality.

The policy options we consider in this study are categorized in six different groups:

1. Post-2012 CO_2 emission reductions in the EU-15
2. Post-2012 CO_2 emission reductions in EU-10 (new EU member states)
3. Post-2012 CO_2 emission reductions in Eastern Europe (including Russia)
4. Hot air sale to the EU-15 during the first commitment period of the Kyoto Protocol
5. Sector inclusion in the EU ETS during the first commitment period of the Kyoto Protocol and onwards
6. Other European climate policies than emission trading (retaining emission targets)

We consider several alternative assumptions for these policy options, listing them Table 2. In the modelling, “post 2012” is treated as the period 2010-2020.

Table 2. Post-2012 policy options as combined in Table 3

Category	Option 1	Option 2	Option 3
Post-2012 emissions in EU-15 and Norway	After KP CP1, emissions are reduced at a rate of 1% year-on-year	After KP CP1, emissions are held constant at KP level through to 2020	
Post-2012 emissions in EU-10	After KP CP1, emissions are reduced by 10 and 20% of BAU in 2015 and 2020 respectively	After KP CP1, emissions are held constant at KP level through to 2020	
Post-2012 policy in Eastern Europe (EE) and Russia	After KP CP1, emissions are reduced by 10 and 20% of BAU in 2015 and 2020 respectively. Regions join EU ETS	After KP CP1, emissions are held constant at KP level through to 2020	After KP CP1, regions follow a no-climate policy emissions trajectory, with no involvement in EU ETS
Hot Air under KP	Hot air sellers restrict supply to maximize revenue	No hot air is allowed	
Sectoral inclusion in ETS[2] (see definitions below)	Current EU ETS inclusion only, for KP CP1 and beyond	Expanded EU ETS for KP CP1 and beyond	Expanded EU ETS for KP CP1, with "Extra" sectors joining in 2015
Climate policy directed outside EU ETS sectors	Small carbon tax to prevent carbon leakage to non-ETS sectors	Carbon tax introduced in 2015 to household, transport, and service sectors	

* KP CP1 = First commitment period of the Kyoto Protocol

** The EU ETS sector inclusion is using the following definitions3:

Current ETS: Gas, electricity, refined oil, iron and steel, concrete
Expanded ETS: Current ETS plus chemicals and aluminium
"Extra" sectors: Other machinery, other minerals, transport equipment, construction
Transport sectors: Land and water transport, air transport

In all scenarios, we assume no emission trading occurs between Europe and the rest of the world. In addition, we also assume no use of the Clean Development Mechanism (CDM). This is to simplify the analysis. Clearly, in reality, substantial greenhouse gas reductions can be achieved through CDM. This would mean that a larger proportion of domestic reductions in SO_2 and NO_x emissions would be required to meet a given air quality target than shown in this report because CDM projects provide no direct air quality co-benefits to Europe. However, the focus of the study is the comparison between the alternative European climate action scenarios – not absolute levels.

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[2] Emission Trading Scheme

[3] In completing this report the Commission released the information that radical changes in the EU ETS would have to wait until after 2012. The ETS may then also be expanded to aviation and CH_4 and N_2O from a few source categories.

We also assume that non-CO_2 Kyoto gases (e.g. CH_4, N_2O, F-gases) will not be featured in the ETS in the Kyoto and post-Kyoto periods up to 2020. This is also for simplicity, but also reflects the complexities related to emission accounting that would need to be overcome in order to include them in the ETS. This is of course an interesting direction for further study, owing to the different relationships between the individual Kyoto gases and air pollutants.

Table 3 lists the eight scenarios generated by GRACE, and their associated policy assumptions. Note: The “no policy” scenario is driven solely by the SRES B2 economic growth and technology assumptions, and assumes no climate action for the entire model horizon. This scenario is given as a reference, but is clearly not realistic. Scenario 2 represents the scenario of future climate change policy in Europe with further reductions in emissions. The scenario features an expanded ETS and a slow reduction of CO_2 emissions beyond the KP. Scenario 3 (not allowing hot air trade the first Kyoto period) does not effect post-2010 emissions and is therefore not discussed further in this report. Scenarios 5 and 6 are equal to scenario 2, but differ with respect to which sectors are included in the ETS. Scenario 7 is the same as scenario 2 in every respect except that the carbon tax is $25/tonne C in 2015 and $50/tonne C in 2020. These prices were chosen ad-hoc, but such that they were reasonable relative to the wider CO_2 permit price.

Scenario 8 represents the withdrawal of Russia and (non-EU) Annex I Eastern Europe Parties from climate policies in the post-Kyoto periods. Thus, the regions feature no CO_2 abatement in 2015 and 2020. We run two versions of Scenario 8 – one in which Russia and Eastern Europe are able to participate in emissions trading with the EU-25 and Norway (in spite of their withdrawal), and one in which they are barred from emissions trading. In the emissions trading case, their “no-climate policy” emissions levels are used as the baseline (but will be slightly different due to carbon leakage).

In most of the analysis in this report, the effect of the climate policies are calculated with reference to S4 (Kyoto continued, keeping emissions at the Kyoto level post 2012). This is because S4 is considered to be a more likely “business as usual” scenario than the “no climate policy” scenario, given the implementation of the Kyoto Protocol and the expressed willingness of the EU to further commitments. The S1 “no climate policy” scenario is shown for comparative purposes.

Table 3. Scenario description

		Policy options					
#	**Scenario**	**Post-2012 emissions in EU-15 and Norway**	**Post-2012 emissions in EU-10**	**Post-2012 policy in EE and Russia**	**Hot Air under KP CP1***	**Sectoral inclusion in ETS**	**Climate policy outside EU ETS**
1	No Policy	BAU	BAU	BAU	n/a	n/a	n/a
2	Further reductions	After KP CP1, emissions are reduced by 1% per year (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	Hot air sellers restrict supply to maximize revenue (Option 1)	Expanded ETS for KP CP1and beyond (Option 2)	Small tax to prevent carbon leakage to non-ETS sectors (Option 1)
3	No Hot Air	After KP CP1, emissions are reduced by 1% per year (Option 1)	After KP CP1, emissions are reduced by 1% per year (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	No hot air is allowed (Option 2)	Expanded EU ETS for KP CP1and beyond (Option 2)	Small tax to prevent carbon leakage to non-ETS sectors (Option 1)
4	KP Continued	After KP CP1, emissions are held constant at KP level through to 2020 (Option 2)	After KP CP1, emissions are held constant at KP level through to 2020 (Option 2)	After KP CP1, emissions are held constant at KP level through to 2020 (Option 2)	Hot air sellers restrict supply to maximize revenue (Option 1)	Expanded EU ETS for KP CP1 and beyond (Option 2)	Small tax to prevent carbon leakage to non-ETS sectors (Option 1)
5	Current ETS only	After KP CP1, emissions are reduced by 1% per year (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	Hot air sellers restrict supply to maximize revenue (Option 1)	Current EU ETS inclusion only, for KP CP1 and beyond (Option 1)	Small tax to prevent carbon leakage to non-ETS sectors (Option 1)
6	Extra ETS sectors	After KP CP1, emissions are reduced by 1% per year (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	Hot air sellers restrict supply to maximize revenue (Option 1)	Expanded EU ETS for KP CP1, with “Extra” sectors joining in 2015 (Option 3)	Small tax to prevent carbon leakage to non-ETS sectors (Option 1)
7	C tax	After KP CP1, emissions are reduced by 1% per year (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	Hot air sellers restrict supply to maximize revenue (Option 1)	Expanded EU ETS for KP CP1 and beyond (Option 2)	Carbon tax introduced in 2015 to household, transport, and service sectors (Option 2)
8	Russian & EE withdrawal**	After KP CP1, emissions are reduced by 1% per year (Option 1)	Emissions are reduced by 10 and 20% of S1 in 2015 and 2020 (Option 1)	No-policy emissions trajectory (BAU) (Option 3)	Hot air sellers restrict supply to maximize revenue (Option 1)	Expanded EU ETS for KP CP1and beyond (Option 2)	Small tax to prevent carbon leakage to non-ETS sectors (Option 1)

* KP CP1 = First commitment period of the Kyoto Protocol. **This scenario is featured both without allowing trade between Russia and Eastern Europe (S8NoT) and with allowing such trade (S8T).

2.5 Relation to CAFE baseline scenario

The CAFE climate policy scenario (Mantzos and Zeka-Paschou, 2004) assumes a carbon price of 20 € per tonne CO_2 in 2020, achieving a 3.6 % reduction of the EU-25 CO_2 emissions in 2020 compared to 1990 (-0.8 % from 2000 to 2020).

In terms of climate policy (i.e. CO_2 emission levels), our S2 scenario ("further reductions") is closest to the CAFE climate policy scenario (CP_CLE). The S2 scenario features Kyoto Protocol implementation in 2010, and a further reduction of EU-25 CO_2 emissions to 2020 of 2.5% less than 2000 levels. However, the absolute level of RAINS-calculated SO_2, NO_x and $PM_{2.5}$ emissions in our S2 scenario differs from the CAFE baseline. This is a result of differing assumptions and structure in the PRIMES and GRACE models, which would result in different region- and sector-level inputs to the RAINS model. As mentioned previously, the GRACE model lacks the technological and activity resolution of the PRIMES model, and thus specific sectoral and technological improvements and activity trends that may appear in PRIMES would not be captured in GRACE. We thus focus on the *relative* values across scenarios and differences between scenarios, where these limitations are less important.

2.6 PM exposure

The effects of fine particulate matter ($PM_{2.5}$) emissions on human health are demonstrated with a national case study. The Finnish Regional Emission Scenario (FRES) model was used to calculate the emissions of primary $PM_{2.5}$ and resulting $PM_{2.5}$ concentrations in different scenarios of this study. The emission calculation of FRES is compatible with the RAINS model. The Finnish population exposure was studied and results qualitatively generalized to the other Nordic countries. The effect on only Finnish emissions was considered, and the background concentrations caused by long-range transport from outside Finland was held constant.

The basic structure of the FRES emission calculation is a combined top-down approach of aggregated area emission source sector description with more detailed bottom-up calculation of large point sources. Large energy production and industrial plants (i.e. plants utilizing boilers with thermal capacity exceeding 50 MW_{th} or plants with emissions >20 Mg $year^{-1}$ (PM, SO_2 or NO_x), 250 plants) are described as point sources with detailed technical description and actual geographical location and stack height information. Area sources include smaller industrial activities, residential combustion, traffic sources and various fugitive dust and other non-combustion sources (102 sectors and 10 fuels). Area source emissions are given with $1 \times 1\ km^2$ spatial resolution for the whole of Finland. A more detailed emission model description can be found from Karvosenoja and Johansson (2003) and Karvosenoja et al. (2005).

The FRES model includes source-receptor transfer matrices for estimating the PM transport and concentrations in Finland. The matrices were developed for several particle size classes and two emission heights (below 50 m and 50 to 100 m) based on dispersion modelling with the Finnish Emergency and Air Quality Modelling System SILAM of the Finnish Meteorological Institute (Sofiev et al 2006). The approach in FRES uses the emissions distributed to the municipalities and large point sources as input, and presents the concentrations in receptor grids with $12 \times 12\ km^2$ resolution as output.

In this study, an index D(exp) was calculated in order to express the differences in population exposure in different scenarios s relative to the S4 scenario (Further reductions in emissions):

$$D(\exp) = \frac{\sum_g \left(c(s)_g \cdot p_g \right)}{\sum_g \left(c(S4)_g \cdot p_g \right)} - 1 \qquad \text{(Equation 1)}$$

Where c = concentration and p = population in grid cells g.

2.7 Cost calculations for avoided costs

We have estimated the costs for alternative technical (end-of-pipe) abatement measures to reach emission reductions for SO_2, NO_x and $PM_{2.5}$ corresponding to our post-Kyoto policy scenarios. These are called *avoided costs*. These costs are represented by the RAINS cost curves as given by RAINSweb (www.iiasa.ac.at). These cost curves reflect the further emission reductions and costs possible after the implementation of the measures given by the CP_CLE baseline scenario developed within the CAFE programme. The end-point of these cost curves illustrates the Maximum Feasible Reduction (MFR) of air pollutants and the maximum annual abatement costs for each nation in the model. The main results are given in chapter 3.2.1.

These cost calculations are contingent on a number of important aspects that need to be considered:

- The costs are taken from the "CP_CLE_Aug04 (Nov04)"-scenario as given by www.iiasa.ac.at/rains.
- The cost calculations in the RAINS cost curves are dependent on the total activity level on which the measure is taken. The activity levels in the RAINS cost calculations are not identical to the activity levels given by our post-Kyoto scenarios, so the alternative costs serve only for comparison since the costs are valid only for CP_CLE activity levels. The different activity levels would affect the shape of the cost curve as well as the end-point emissions and costs.
- In the case where the emission reduction in the scenario exceeds the emission reduction available by MFR, the maximum MFR cost is used to estimate avoided costs. The consequence of this is that the avoided costs resulting from using RAINS are underestimations in these cases. This, of course, highlights the limitations of using technical abatement measures instead of fuel switching to reduce air pollutant emissions.
- All RAINS measures, except measures in the mobile sector, must be implemented to the degree set by the RAINS cost curve. The result is that the RAINS costs are given for more stringent emission reductions than in the climate policy scenarios. So the RAINS costs are overestimations in these cases.
- The mobile sector is introduced into the NO_x cost curve by calculating the unit abatement cost of NO_x when moving from CP_CLE emissions to MFR emissions from the mobile sector. The measures in the mobile sector are introduced into the NO_x cost curve as one measure and ranked by comparing the unit abatement cost of the mobile sector with the marginal abatement cost for the other measures in the cost curve.[4]
- The lower bound on the RAINS cost curves is used to obtain the emission reduction for each scenario, which leads to underestimations of the corresponding costs.

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[4] The first measure of any sector has a unit (average) cost that equals its marginal cost. So by treating the measures in the mobile sector as one measure, the unit cost equals the marginal cost and the mobile sector can be ranked accordingly.

- In the scenarios, no measures are taken in the international sea transport sectors, only national measures are accounted for. Thus no RAINS measures for international sea transport were carried out.
- In the cases where emissions increase in a scenario, the costs are set to zero. The other option would be to allow for less stringent air quality policies in the affected countries.

2.8 Macro-economic Cost Estimates

The consequences for the "economy-at-large" from the different ambition levels and regional and sectoral distribution of CO_2 abatement are estimated by comparing the changes in welfare induced by different CO_2 abatement strategies.

Welfare changes are calculated as equivalent variation (EV): the income compensation required to purchase the new bundle of goods at the old prices. When undertaking this calculation, we correct the income first for the allocation of CO_2 emission permits – which generates a false economy, similar to that of Bastiat's (1850) Parable of the Broken Window. This correction subtracts the value of the permit endowment in each period from the regional household's nominal income.

The welfare changes are estimated for the aggregated regions 'Nordic Countries', 'Rest of EU-25', 'Poland and the Baltic States' and 'Rest of Europe and Russia'. The cost estimates for all parameters are given for the year 2020 and are expressed as per cent deviation from the situation in scenario S4. The main results are presented in chapter 3.2.2. Of importance for the macro-economic analysis is that the deviation from S4 is calculated on the total value for an entire macro region, not as the average deviation of all the sub-regions.

Furthermore, economic welfare estimates are always a bit controversial. In this study we assume that the welfare effects of CO_2 abatement will be strictly financial for all parties affected by the various post-Kyoto scenarios. We assume that no welfare effect will occur from changes in health, environment or other parameters induced from the improved air quality featured in our scenarios. Neither do we take into account any life-style effects other than the one connected to financial trade offs.

Table 4. Regions in the macro economic analysis

Macro regions	GRACE regions
Nordic Countries	DEN, FIN, NOR, SWE
Rest of EU-25	FRA, GER, MED, REU, UKI
Poland and Baltic states	BAL, POL
Rest of Europe and Russia	REE, RUS

3 Results

3.1 Emissions

3.1.1 CO_2 emissions

Emission data tables are given in Annex 2. CO_2 emissions 2000-2020 for the alternative scenarios are illustrated in Figure 2. CO_2 abatement policy is assumed to undertake a cap-and-trade format within the participating regions (Nordic regions, rest of EU, and rest of Europe including Russia). Abatement occurs within the ETS sectors or taxed sectors (see Table 2), and in all scenarios (except S7, which studies the effect of a larger tax on non-ETS sectors) a small carbon tax is applied to the remaining sectors to prevent carbon leakage. There of course may be redistribution between the sectors and regions as a consequence of the scenario setup.

All scenarios feature reduced European CO_2 emissions compared to the no-policy scenario (S1). The only exception is the scenario in which the rest of Europe abandons carbon caps, and does not trade with the Nordic and EU countries (S8NoT). The scenario features carbon leakage towards the rest of Europe group, and thus increases their emissions relative to the no-policy scenario.

The level of future CO_2 reduction commitments (as illustrated in S2, which assumes further year-on-year reductions after 2010 compared to S4, which keeps emissions at the Kyoto level) is evidently important to determine future emissions in all regions. Emissions in the whole region studied are reduced by 10% from 2000 to 2020 in S2 and by 3% in S4. CO_2 emissions are in relative terms reduced most in Russia and Eastern Europe, followed by the EU-25[5] and the Nordic countries. This distribution is as expected, given the relative marginal abatement costs in each country. The EU and Nordic countries will purchase credits from the rest of Europe.

Expansion of the emission trading scheme with more sectors will only have small, distributional effects, because the overall emissions cap is kept constant. Expansion of the ETS leads to further reduced emissions in Russia and Eastern Europe, and increased emissions in the Nordic and EU-15. However, the difference between the expected expanded ETS and addition of extra sectors (S2 vs S6) is insignificant in terms of changing regional CO_2 emissions. Taxes on additional sectors (transport, and household) lead only to a small shift in emissions from the Nordic countries and EU-25 to the rest of Europe.

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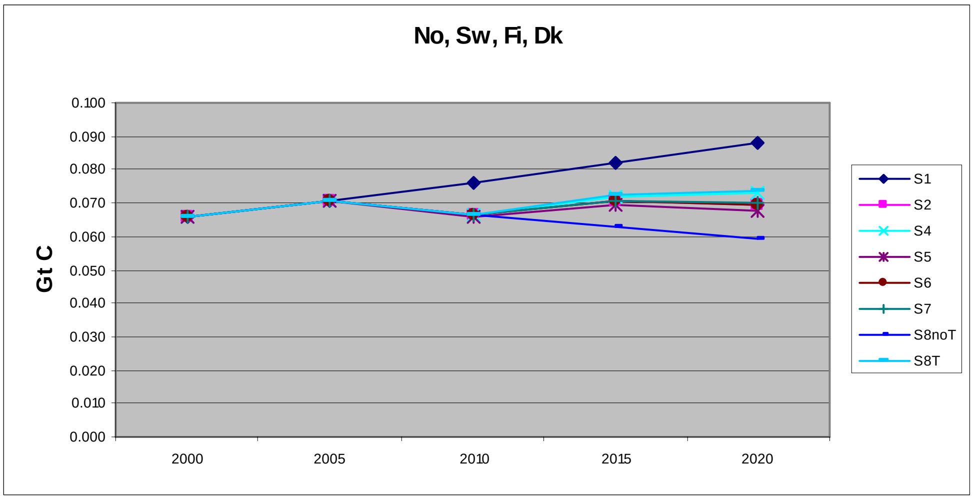
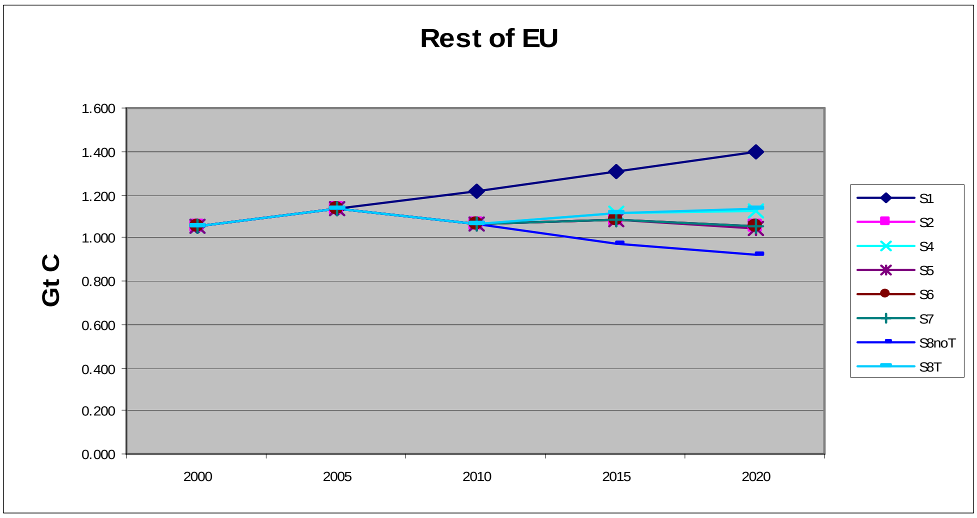
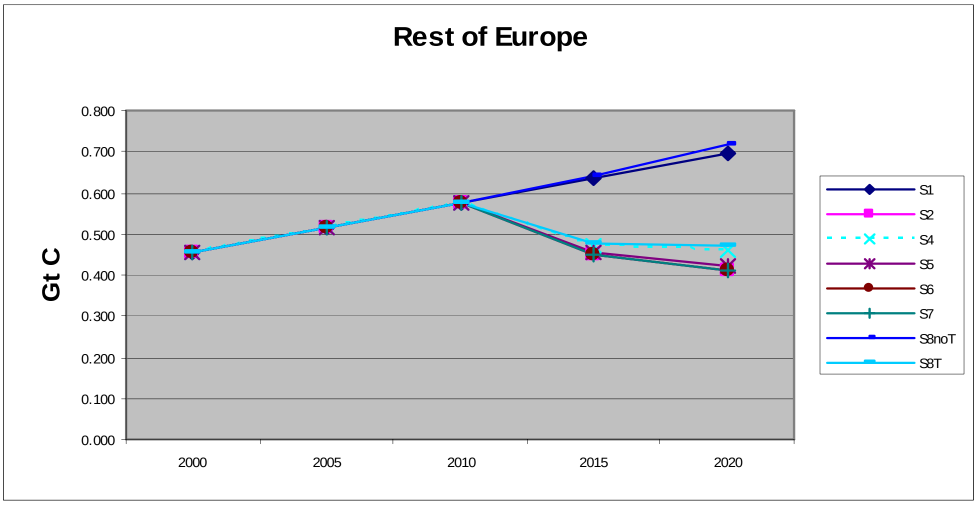
[5] Here and in the following EU-25 excludes Denmark, Finland and Sweden.

Figure 2. CO_2 emissions for each scenario







3.1.2 Emissions of air pollutants

Emissions in 2020 for the various scenarios relative to S4 (Kyoto continued) are illustrated in Figure 3, 4 and 5 for SO_2, NO_x and $PM_{2.5}$, respectively[6]. Note that the assumptions regarding end-of-pipe abatement are the same for each scenario, so we isolate the impact on air pollutants emissions for each of the climate policy options. As expected, we see a noticeable correlation between CO_2 abatement and reductions in emissions of SO_2. The effect on NO_x and PM emissions from climate policy is generally less pronounced than for SO_2. The same trend is seen in the CAFE baseline. We focus here on the differences between the options for post-Kyoto policies on the emission level in the regions considered (the period 2010 to 2020).

The effect of caps

The S4 scenario (Kyoto continued), which assumes emissions will remain at the level of the first commitment period after 2012, gives higher air pollutant emissions in all regions compared to S2 (further reductions). Comparing the S4 (Kyoto continued) with S1 (no climate policy) or S2 scenarios for SO_2, we see the largest emission reduction from implementation of a stricter climate policy occurs in EU-10 and Eastern Europe/Russia, followed by the EU-15[7] and the Nordic countries. This is a result of the location of where the CO_2 reductions are taking place – where costs are lowest. For NO_x, the S2 scenario gives the highest reductions in EU-10. The effect of climate policies on $PM_{2.5}$ emissions is generally small with the exception of the Nordic countries (no climate policy vs. Kyoto Protocol target levels until 2020).

The effects of taxes and including additional sectors

Comparing scenarios S5 (current ETS) and S6 (expanded ETS with extra sectors) with S2 (expanded ETS)[8], we find that the expansion of the sectoral inclusion in the EU ETS generally leads to a small increase in emissions of SO_2 and $PM_{2.5}$ and an even smaller increase in emissions of NO_x. This result is driven by the distributive effect of changing the sectoral inclusion in the ETS. The sectors included in the ETS (the power, iron and steel, and concrete sectors) are key emitters of SO_2. By expanding the ETS to include additional sectors (e.g. aluminium, concrete, chemical, minerals), CO_2 reductions are distributed away from the key SO_2 emitters (because CO_2 reductions are less costly in the additional sectors), towards sectors that do not emit SO_2 in such proportions. As such, while the total CO_2 reductions remain the same, expanding the ETS will in fact reduce the impact on air pollutant emissions. The effect of adding extra sectors (S6) is insignificant for SO_2 and NO_x. For PM, adding the extra sectors (S4 to S6) increases emissions by an equal or slightly larger amount than the first expansion (S5 to S2).

An increase in emissions is also seen when a tax is implemented on the transport, service and household sectors (comparing S7 to S2) (with the exception of NOx and PM in rest of Europe). This tax generally redistributes further the burden of CO_2 abatement to sectors that are not large sources of air pollutants emissions. The difference between these four scenarios is generally very small and partly insignificant. A fuel tax may enhance PM emission, for example, if it results in increased domestic wood combustion.

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[6] Emission data tables are given in Annex 1.

[7] EU-15 is here exclusive the Nordic member states.

[8] The cap on emissions is the same in all of these.

The effect of non-EU climate policies

The S8 scenario illustrates the effect of EU-25 and Norway undertaking climate policies with further reductions in emissions in the post 2012 period, while Russia and Eastern Europe do not. In the case where there is no trade between the regions (S8NoT), this would result in large reductions in SO_2, NOx and PM emissions in the Nordic countries and EU-15, while emissions in the rest of Europe increase. This is because no trading with Russia and Eastern Europe would require that the EU and Nordic countries undertake more abatement at home to reach their climate targets. The effect on PM emissions is smaller than for SO_2 but larger than for NO_x. Allowing trade between the regions would result in increased air pollutant emissions in all regions, and in particular in the rest of Europe and EU-10. It should be noted that allowing such trading without links to GHG emission caps or projects aiming at emission reductions is not realistic.

3.1.3 PM emissions in Finland

PM effects on concentrations that are calculated as a case study with a Finnish regional model depend, in addition to country total emissions, also on the spatial distribution of emissions. The spatial distribution of emissions again depends partly on the relative contribution of different sectors. Therefore, the relative differences in sectoral emissions are given for Finland in Figure 6.[9] In general, the relative changes compared to S4 are relatively similar in different sectors.

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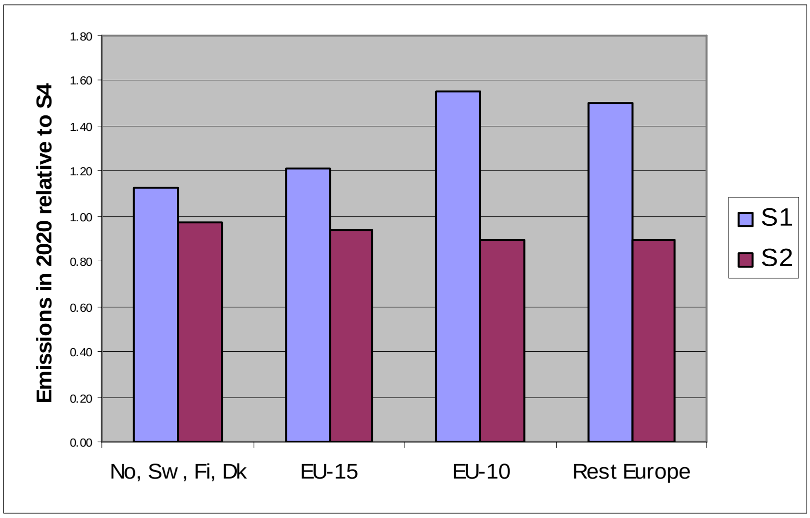
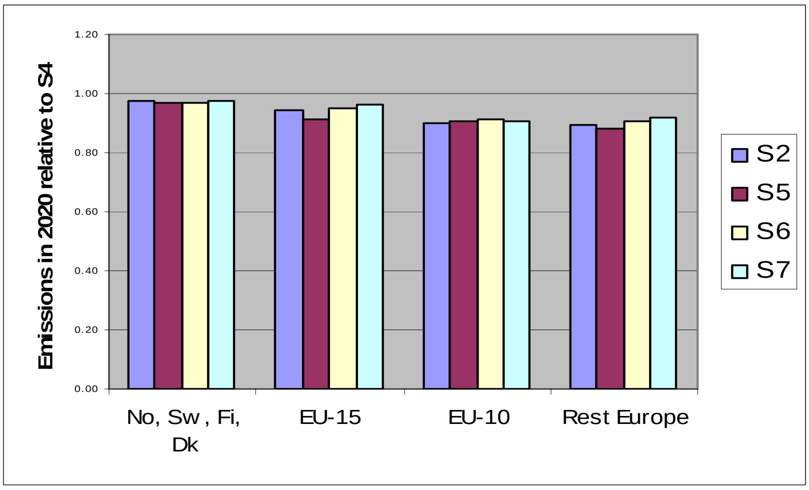
[9] Data tables are presented in the Annex.

Figure 3. SO$_2$ emissions in 2020 relative to S4

The effect of caps



The effects of taxes and including additional sectors



The effect of non-EU climate policies

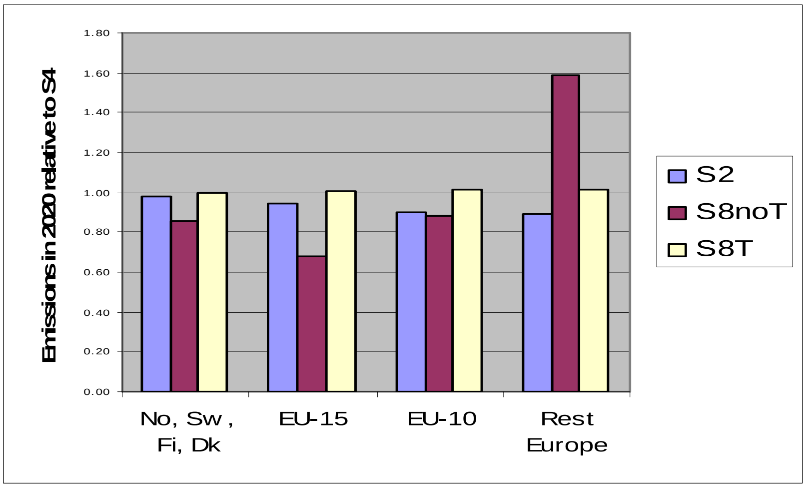
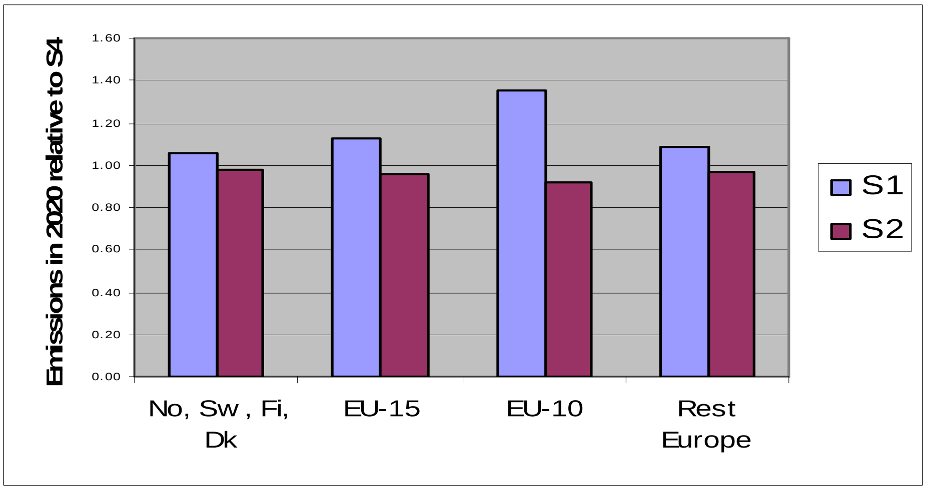
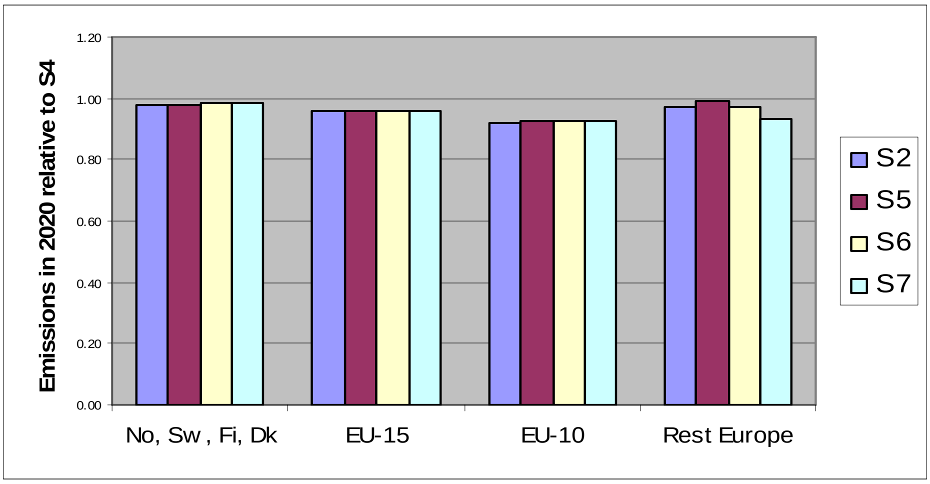


Figure 4. NO_x emissions in 2020 relative to S4

The effect of caps



The effects of taxes and including additional sectors



The effect of non-EU climate policies

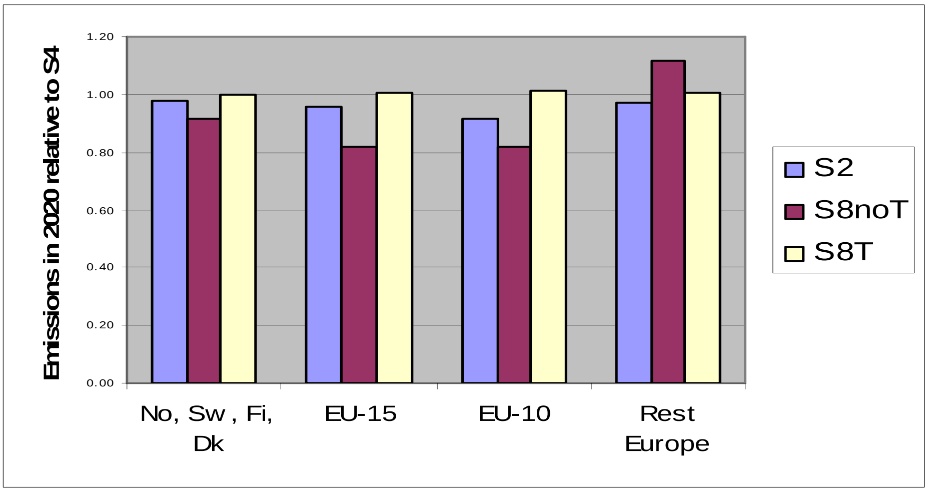
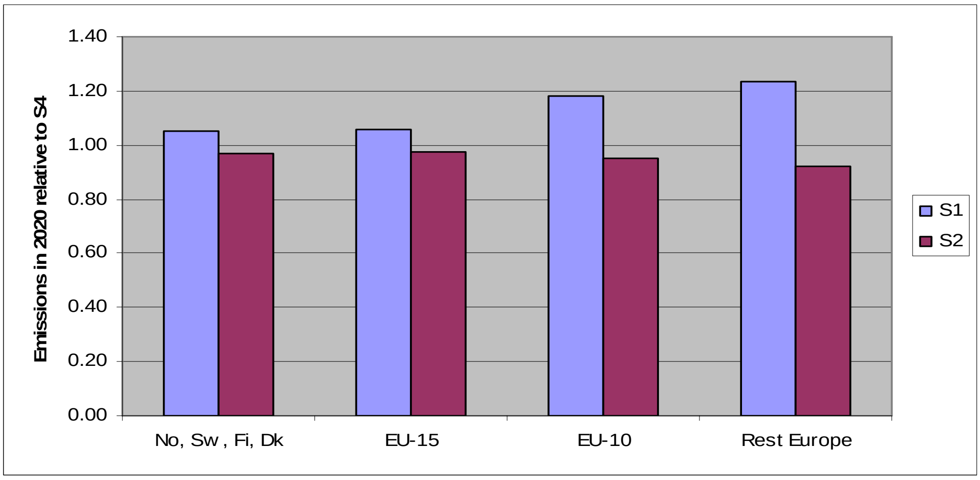
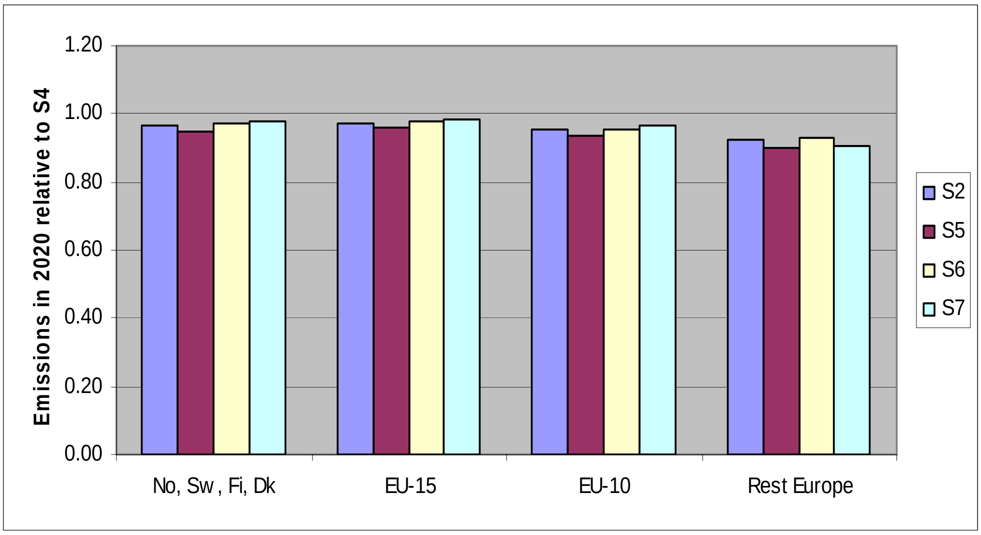


Figure 5. PM$_{2.5}$ emissions in 2020 relative to S4

The effect of caps



The effects of taxes and including additional sectors



The effect of non-EU climate policies

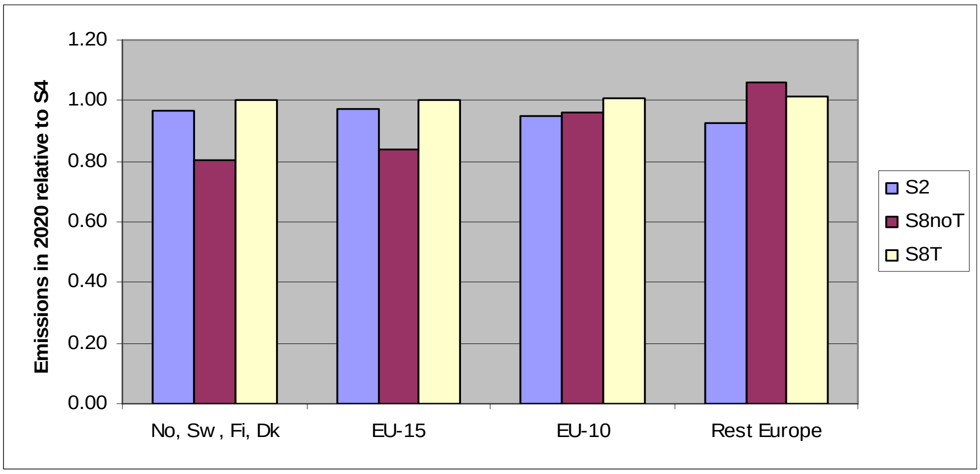
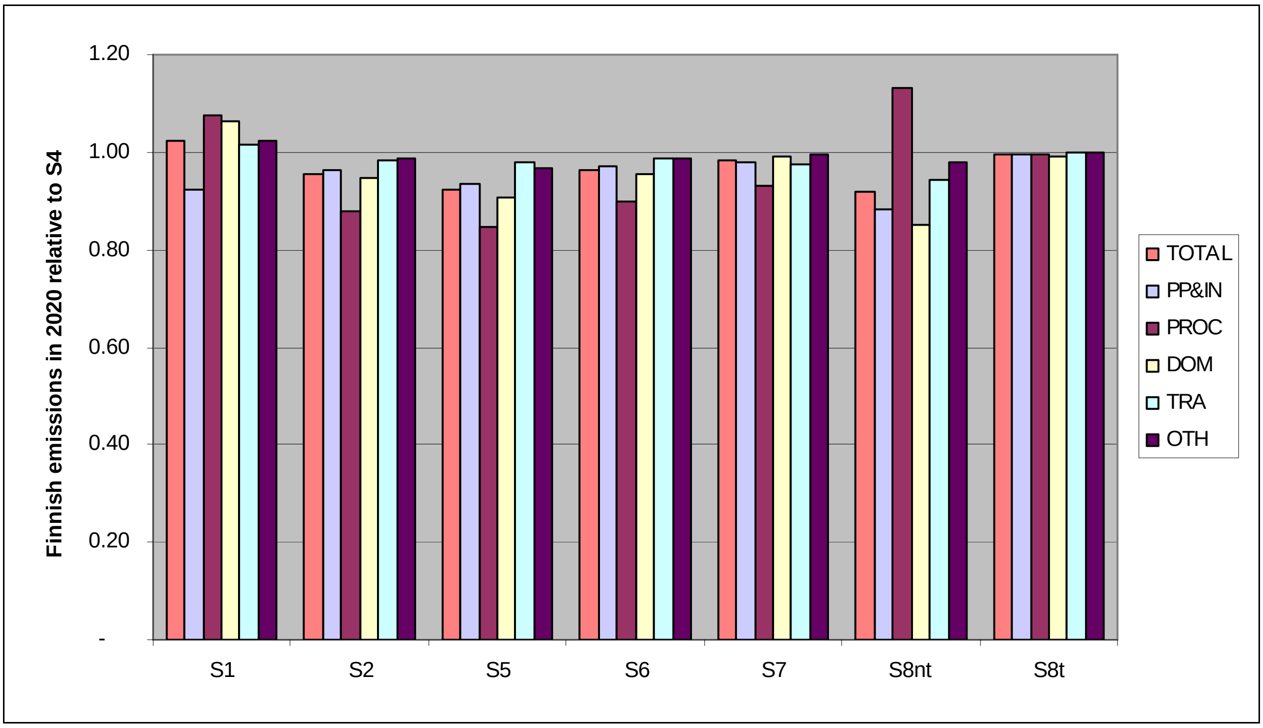


Figure 6. Sector share of emissions in Finland relative to S4



3.2 Costs

3.2.1 Avoided emission reduction costs

The avoided emission[10] reduction costs are an approximate illustration of *how much it would cost the European countries to reach air pollution emission reductions similar to the ones acquired in the examined post-Kyoto scenarios, if the emission reductions were to be reached by technical measures directly developed to abate* SO_2, NO_x *and* $PM_{2.5}$. The emissions are compared to the emissions in scenario S4 and the costs are calculated by using the abatement cost curves for SO_2, NO_x and $PM_{2.5}$ as given by the MFR scenario in RAINSWeb. Further details are presented in chapter 2.7. These costs may be regarded as avoided costs.

The avoided costs reflect the level of emission abatement compared to S4 and are in most cases correlated with emission reductions achieved in the different regions. In some cases, the aggregated costs can appear to be inconsistent with emission reductions, but this is an effect of the chosen aggregation method and the fact that no negative costs are included in the cost estimates. For example, in the region “Rest of Europe and Russia” and scenario S1, the avoided costs are € 15 million while the annual emissions actually increase. The positive cost is a result of the fact that on a disaggregated level some abatement occurs in one of the sub-regions while in the other sub-region no cost savings from decreased emission levels are accounted for.

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[10] In this chapter, “emissions” refer to emissions of SO_2, NO_x and $PM_{2.5}$ if nothing else is explicitly mentioned

From the tables 5 and 6, the following observations can be made:

The avoided costs to reach the emission level of each scenario only differ slightly between the scenarios. The costs are highest for S8NoT and S7. The distribution of abatement costs are evenly distributed between EU-25 and the rest of Europe in S2. In S5, the effect of further CO_2 reductions without increasing the ETS sectors is illustrated. The sole effect of not expanding the ETS is best illustrated by comparing the abatement costs and effects for S5 and S6. Overall there is a small effect on total costs from expanding the ETS. However, it can be seen that the expansion of the ETS decreases total avoided costs as well as changes the distribution of costs between EU-25 and the rest of Europe and Russia. The ETS expansion lowers the avoided costs, which is an indication of the fact that SO_2 reductions are smaller in S6 than S5, as mentioned in chapter 3.1.2. So by including more sectors in the ETS, some synergy effects between SO_2 and CO_2 abatement will be lost.

The effect of a carbon tax in the non-trading sectors (S7) would result in an increased effort in NO_x abatement in “Rest of Europe and Russia” (compared to S2) with the consequence that the region would be assigned most of the avoided costs for emission abatement. S7 is in this part of the analysis the second most costly option when measuring alternative costs on top of S4, but it is the best on NO_x abatement, second best on PM abatement and third best in SO_2 abatement.

If Eastern Europe and Russia were to withdraw from any mandatory CO_2 reductions and not participate in any ETS (S8NoT), the avoided costs within EU-25 to reach the same emission level would be extremely large. NO_x abatement in EU would reach their highest levels of emissions of the options considered. At the same time, the region “Rest of Europe and Russia” would increase its emissions of SO_2 and NO_x to levels even beyond S1. So the overall effect in Europe on top of S4 would be that the costs are the highest while the total emissions of SO_2 increases and the abatement of NO_x and $PM_{2.5}$ are very moderate.

If “Rest of Europe & Russia” were to be allowed in the trading system without any CO_2 obligations, the alternative abatement costs would be close to zero although “Rest of Europe and Russia” would perform some very small abatement efforts on SO_2. It appears as if the other regions can cover their CO_2 abatement obligations fully by purchasing emissions from the “Rest of Europe and Russia”. These CO_2 abatement measures seem to have a very small effect on SO_2 since Russia and Eastern Europe do not have any cap on their emissions. It should be noted that this scenario is on the extreme side. It would be more realistic that such trading would be limited and be on a project level to ensure reductions in CO_2 emissions, in which case co-benefits in reduced air pollutants emissions might have been larger.

Of importance in the avoided cost calculations shown in table 5 is that they are based on underestimated quantities of the alternative emission reductions. One reason for this is that the methodology used for cost estimations underestimates the costs corresponding to the emission reduction levels. The other reason is that in some cases the scenario-specific emission reduction exceeds the available end-of-pipe technical emission reduction potential as suggested by RAINSweb. The effect of this is that the co-benefits from CO_2 abatement strategies and the regional distribution effects are underestimated.

Table 5. Emissions reductions in 2020 (relative to S4) on which the avoided costs are calculated (ktonnes/year)

	No, Sw, Fi, Dk			EU- 15			EU-10			Rest of Europe			Europe		
	NO_x	SO_2	$PM_{2.5}$	NO_x	SO_2	$PM_{2.5}$	NO_x	SO_2	$PM_{2.5}$	NO_x	SO_2	$PM_{2.5}$	NO_x	SO_2	$PM_{2.5}$
S1	-38	-26	-6	-690	-631	-41	-259	-644	-34	-565	-3323	-475	-	-	-
S2	12	5	4	223	170	19	60	-26	9	205	593	155	500	791	188
S5	14	6	6	234	269	31	55	107	13	38	815	208	341	1197	258
S6	11	6	3	218	160	17	53	103	8	176	658	141	458	927	169
S7	11	5	2	220	126	14	54	112	7	435	575	190	720	818	213
S8 NoT	54	29	22	995	998	122	133	132	7	-758	-4075	-122	424	-2916	30
S8T	-1	0	0	-30	-27	-2	-7	-14	-1	-20	55	-32	-58	14	-36

* Emission reductions in this table are not fully consistent with emission data in Annex 2 because increases in emissions occurring at the aggregation level of the analysis are not accounted for.

Table 6. Avoided costs in 2020 (relative to S4) derived using RAINS technical measures (Mill. €)

	No, Sw, Fi, Dk	EU 15	EU -10	ROE	Europe
S1	0	3	0	15	**18**
S2	7	156	37	200	**401**
S5	16	199	67	182	**463**
S6	7	132	54	180	**373**
S7	6	134	60	434	**634**
S8NoT	190	5040	407	14	**5651**
S8T	0	0	0	0	**0**

3.2.2 Macro-economic welfare effects

The values presented in this chapter represent the difference between the studied scenario and the scenario S4 for welfare effects. The unit is given in per cent. Although most differences between scenarios are small for the aggregated regions, some larger changes within the GRACE regions can be hidden since they are cancelled out by opposing changes or are swamped by the pure size of the economy within which the changes occur.

Of interest for the discussion on welfare effects is the actual effect on emissions and permit prices from the different strategies. To simplify comparison, the emissions reductions compared to S4 of CO_2, SO_2, NO_x and $PM_{2.5}$ for Europe in 2020 are presented in Table 7, and the permit prices in Table 8. To avoid confusion, the prices are quoted in both $/tonne C and $/tonne CO_2 terms.

The reason why the CO_2 emission reductions from S4 are identical for S2 to S7 is that they all have exactly the same emission reduction target, as can be seen in Table 3. Furthermore, the regions included constitute all Europe as well as the Baltic States and the Russian parts of Europe.

Table 7. Emission reduction from emission levels in S4, Europe 2020

	CO_2 Gtonnes C	SO_2 ktonnes	NO_x ktonnes	$PM_{2.5}$ ktonnes
S1	-0.524	-4624	-1552	-133
S2	0.120	741	500	117
S5	0.120	1197	341	148
S6	0.120	927	458	148
S7	0.120	818	720	166
S8 NoT	-0.039	-2916	424	62
S8 T	0.018	14	-58	-41

Table 8. 2020 Permit price for CO_2 (2000US$)

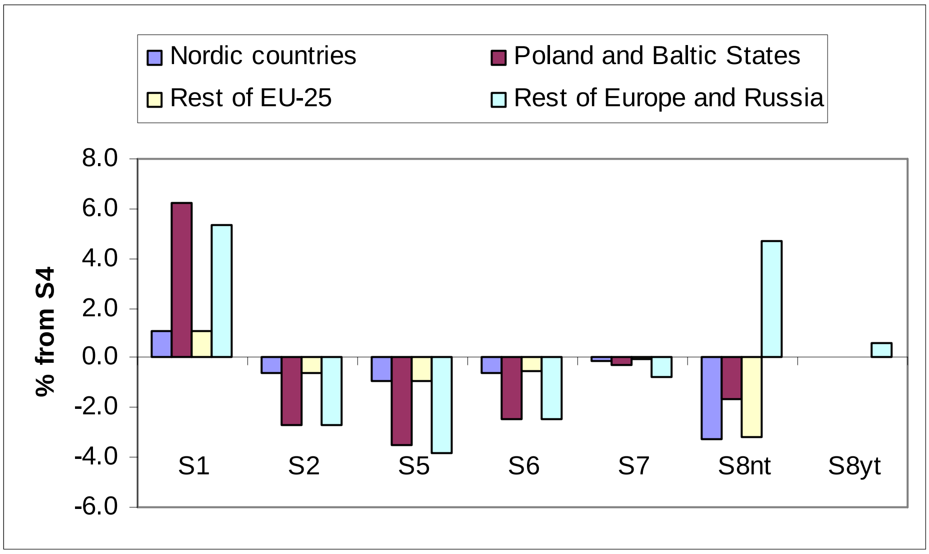
	$/tonne C	$/tonne CO_2
	2020	**2020**
S1	-	-
S2	501	137
S4	278	76
S5	715	195
S6	478	131
S7	399	109
S8NoT	3109	849
S8T	255	70

Table 8 shows the carbon prices corresponding to the scenarios examined with a top-down CGE model, GRACE. These carbon prices are the result of a trading system that doesn't take into account any Clean Development Mechanism (CDM) or Joint Implementation (JI) activities. The emission trading is for Europe only, without taking into account any trading with America or Asia. Furthermore, the emission reductions for Eastern Europe and Russia are fairly ambitious (year 2000 emissions -20% in 2020).

The permit prices in Table 8 present a large range for 2020. The values are dependent on the participation, stringency, and ETS setup of the scenarios. We find the results to be reasonable. In particular, scenarios S2 and S4 are comparable with the 2020 permit prices and carbon limits of the CP (current policy) and DCM (deep cuts) from PRIMES featured on RAINSWeb (http://www.iiasa.ac.at/web-apps/tap/RainsWeb/).

The welfare effects from the different trading schemes analyzed in scenarios 1 to 8 are well correlated with the permit price (Table 8) and total reduced CO_2 emissions (Table 7). The levels are within a reasonable range, and similar to those featured for similar abatement levels in the EPPA4 CGE model (Paltsev et al., 2005). The welfare impact on the Rest of Europe regions is larger than for the Nordic and EU countries as a consequence of their higher carbon intensity of GDP. This leaves them more ‘vulnerable’ to carbon limits compared to service-centred economies such as those in the EU.

Figure 6. Welfare effects in 2020 of alternative scenarios to S4



Comment: Welfare change is calculated as equivalent variation, adjusted for consumer prices and the income from the initial permit endowment.

Figure 6 compares welfare impacts relative to scenario S4. S5 has the highest negative effect on welfare for the regions (other than S8NoT). This is a result of its restricted ETS inclusion, which limits abatement to few sectors. S2 and S6 are fairly similar in welfare changes although S6 has a larger impact on SO_2 emissions. S7 has a comparatively limited effect on welfare, which is a consequence of the not very effective reduction of CO_2 emissions. However, S7 is the second most effective scenario regarding NO_x abatement and the third most effective for SO_2.

S8NoT is considered as a special case where the supply of potential CO_2 emissions is much lower than in the other scenarios. “Rest of Europe and Russia” experiences a very strong welfare effect relative to S4, correlated with abandoning carbon limits. It should be noted that the region does not, however, regain the welfare levels in the no-policy scenario, S1. This is a consequence of the negative impact from reduced welfare and economic activities in the other regions.

Of interest is also the effect on welfare and CO_2 prices from the expansion of the ETS (compare S5 to S6). It can be seen that the carbon prices in S6 are much lower than in S5, and the welfare effects act correspondingly.

For clarity, the “Regional Household” is what in the GRACE model represents governmental, corporate and household activities.

3.3 Environmental effects

To illustrate the changes in environmental impacts of emissions, we have calculated the environmental effects using the effect module of RAINS and the Finnish model on exposure to PM. We show the effects for 2020 only. Focus is on acidification, eutrophication, ozone effects on vegetation and health effects from PM exposure.

3.3.1 Acidification

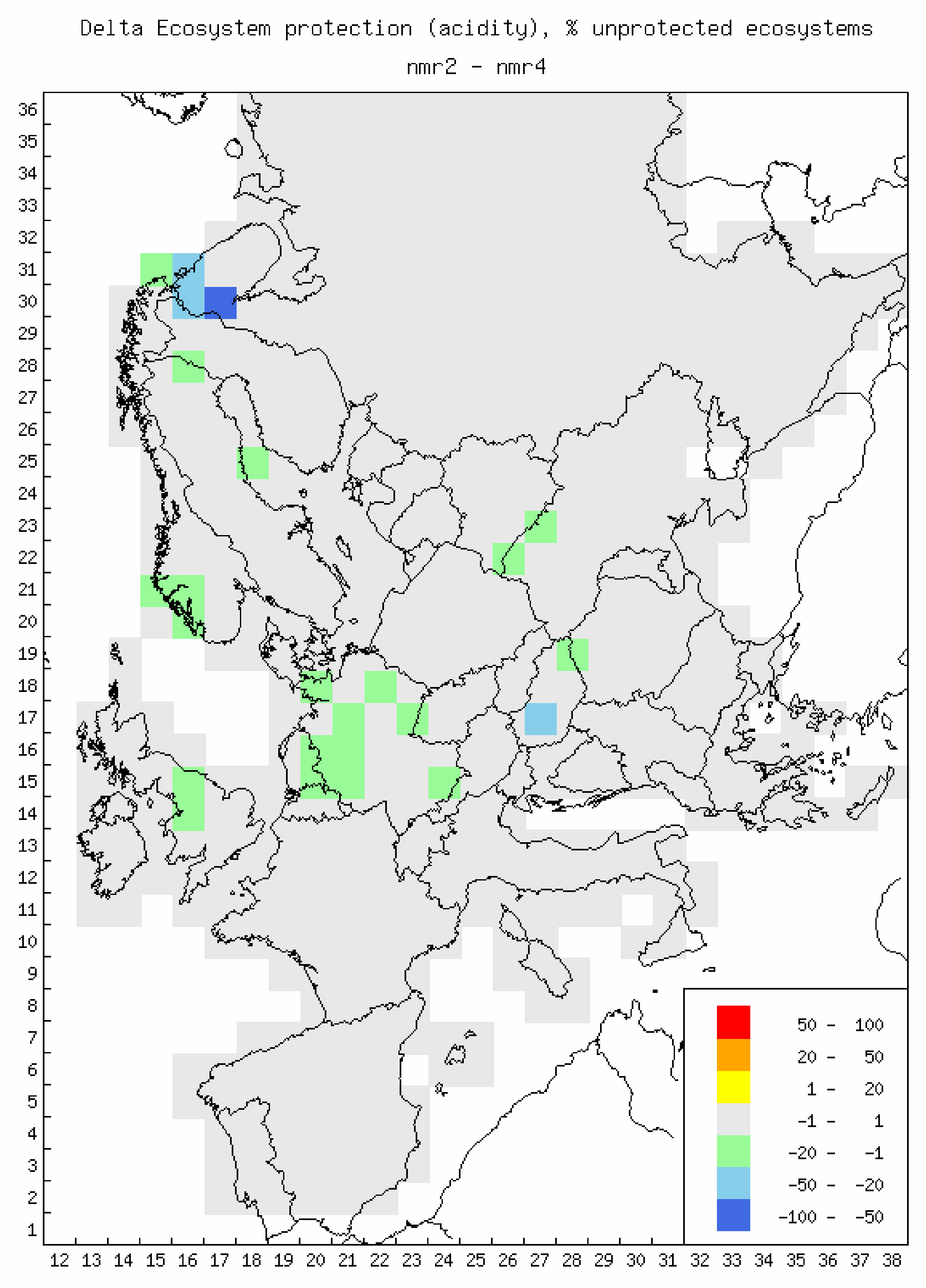
The changes in the effects of acidification are illustrated using changes in ecosystem protection for acidity (% unprotected ecosystems) as an indicator. The critical load is a defined limit to how much nature can receive of air pollution without damage. The exceedance (measured as % unprotected ecosystems) is the excess of current deposition loads over critical load. Selected maps are shown in Figure 7 below.

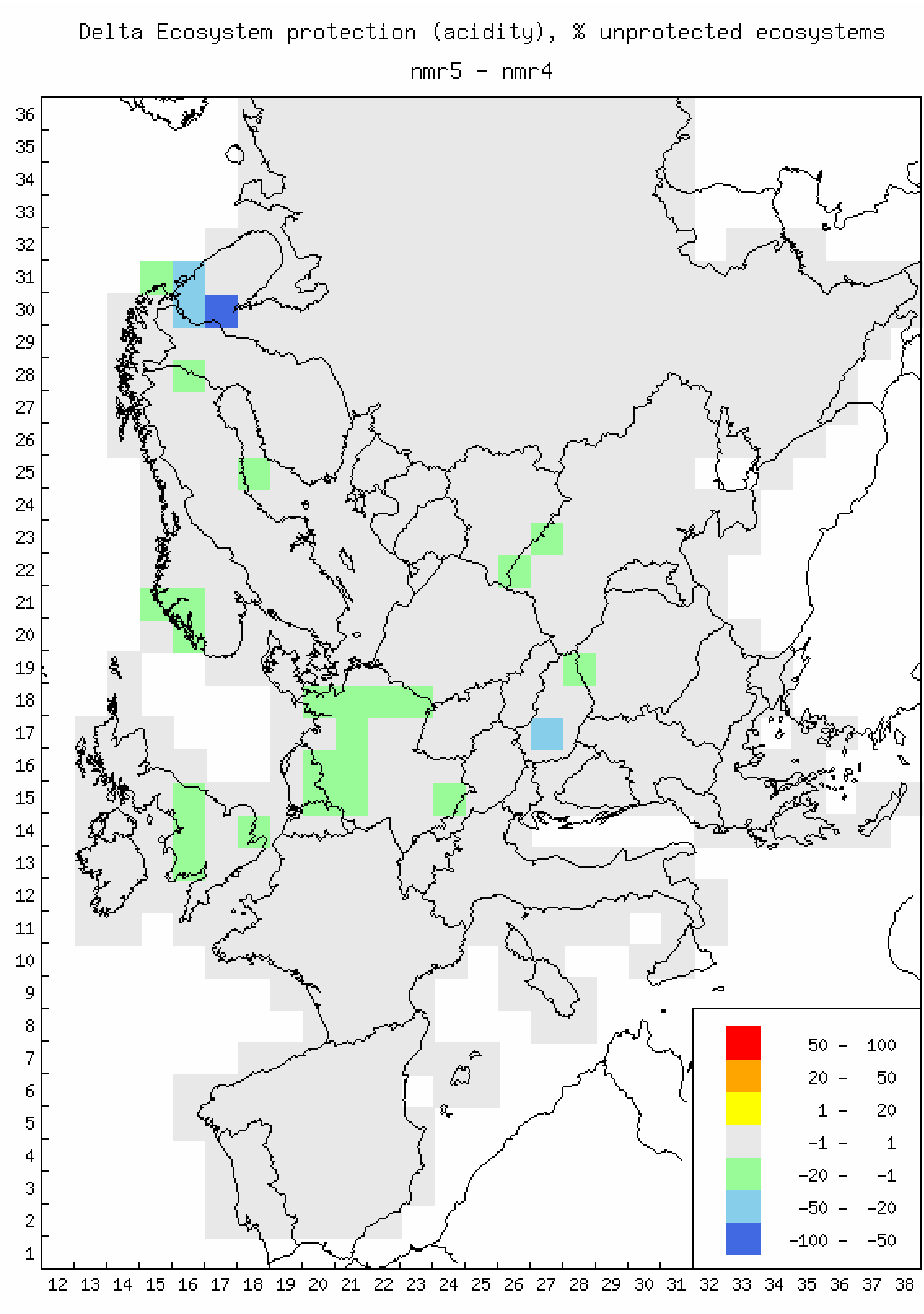
Further reductions in CO_2 emissions undertaken after 2012 (comparing S2 further reductions with S4 Kyoto continued) will imply small reductions in unprotected ecosystems in southern Norway, north-eastern part of Sweden, Finland and Norway and parts of UK and Germany. The largest reductions will be in the Kola area of Russia. There are few changes other places in Russia and Eastern Europe, since there already are few unprotected ecosystems here. The largest benefits will be in the Nordic countries and Russia.

The difference in effects of S2, S5, S6 and S7 are not large (as expected from the small changes in emissions). Expansion of the ETS (S6) gives less benefit in reduced acidity over Norway and a couple of other places compared to the current ETS (S5). With a tax added to non-ETS sectors, the per cent of unprotected ecosystems also increases (slightly worse than S6).

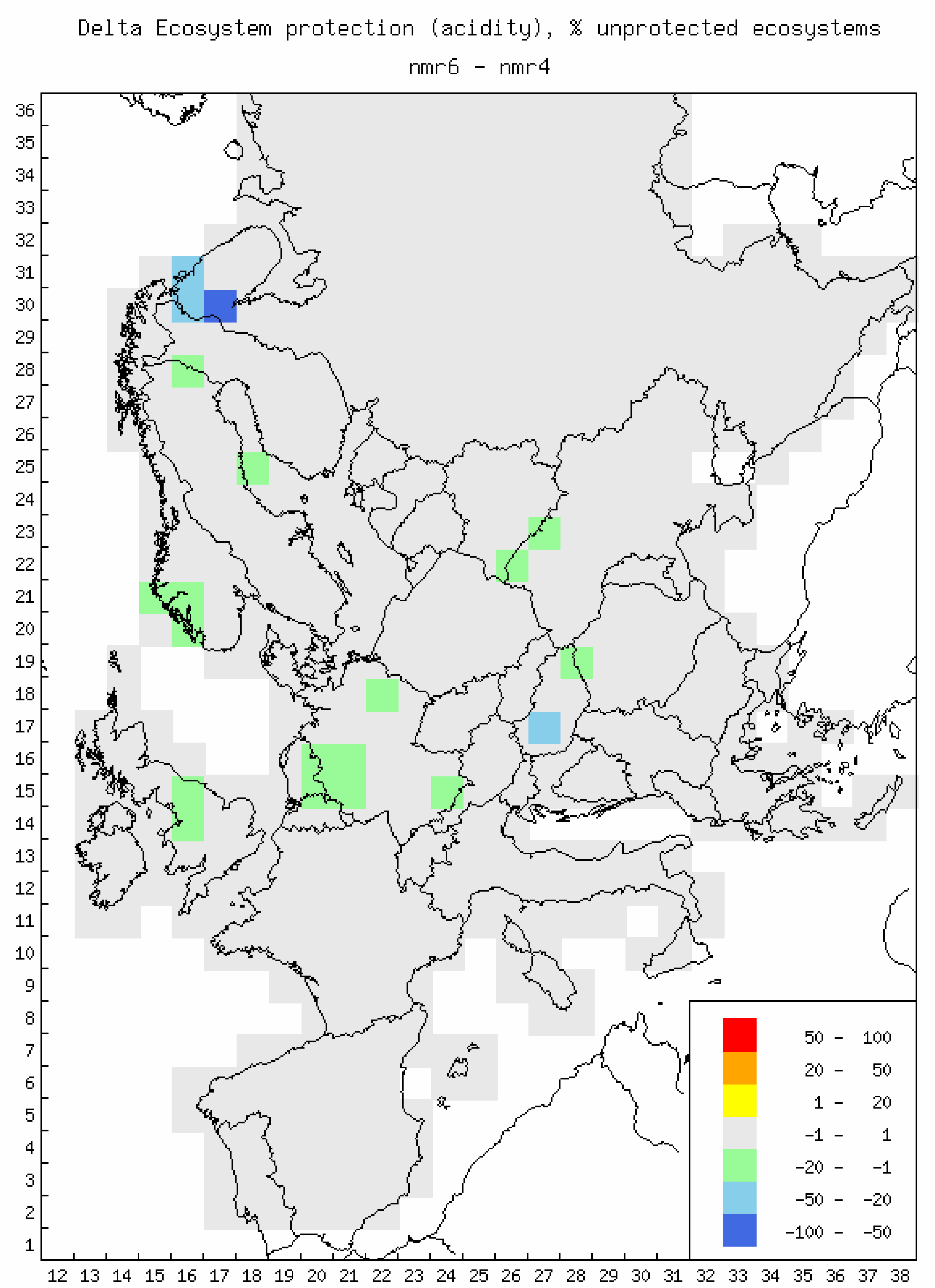
Scenario 8 *without* trade will, compared to keeping emissions at the Kyoto level in all regions, increase the per cent of unprotected ecoystems in Russia and Eastern Europe, but also in Northern Scandinavia. The areas of unprotected ecosystems in EU-15 (Germany and UK in particular) and southern Scandinavia will decrease. Scenario 8 *with* trade will imply a small increase in per cent unprotected ecosystems over S4 in all regions.

Figure 7. Acidity: changes in ecosystem protection




Delta Ecosystem protection (acidity), % unprotected ecosystems

nmr5 - nmr4


Delta Ecosystem protection (acidity), % unprotected ecosystems
nmr6 - nmr4
36
35
34
33
32
31
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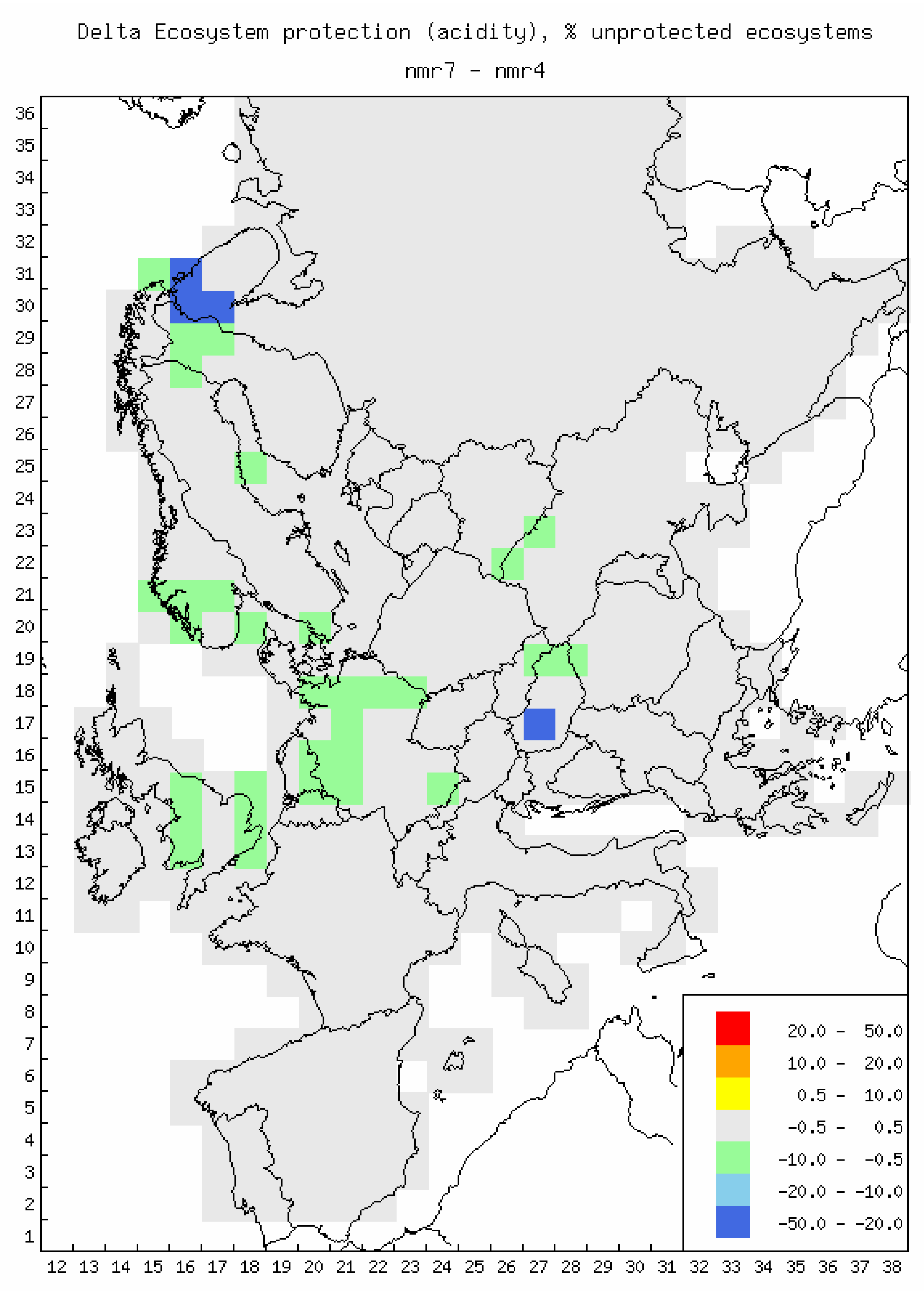
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
50 - 100
20 - 50
1 - 20
-1 - 1
-20 - -1
-50 - -20
-100 - -50


Delta Ecosystem protection (acidity), % unprotected ecosystems
nmr7 - nmr4
36
35
34
33
32
31
30
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28
27
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25
24
23
22
21
20
19
18
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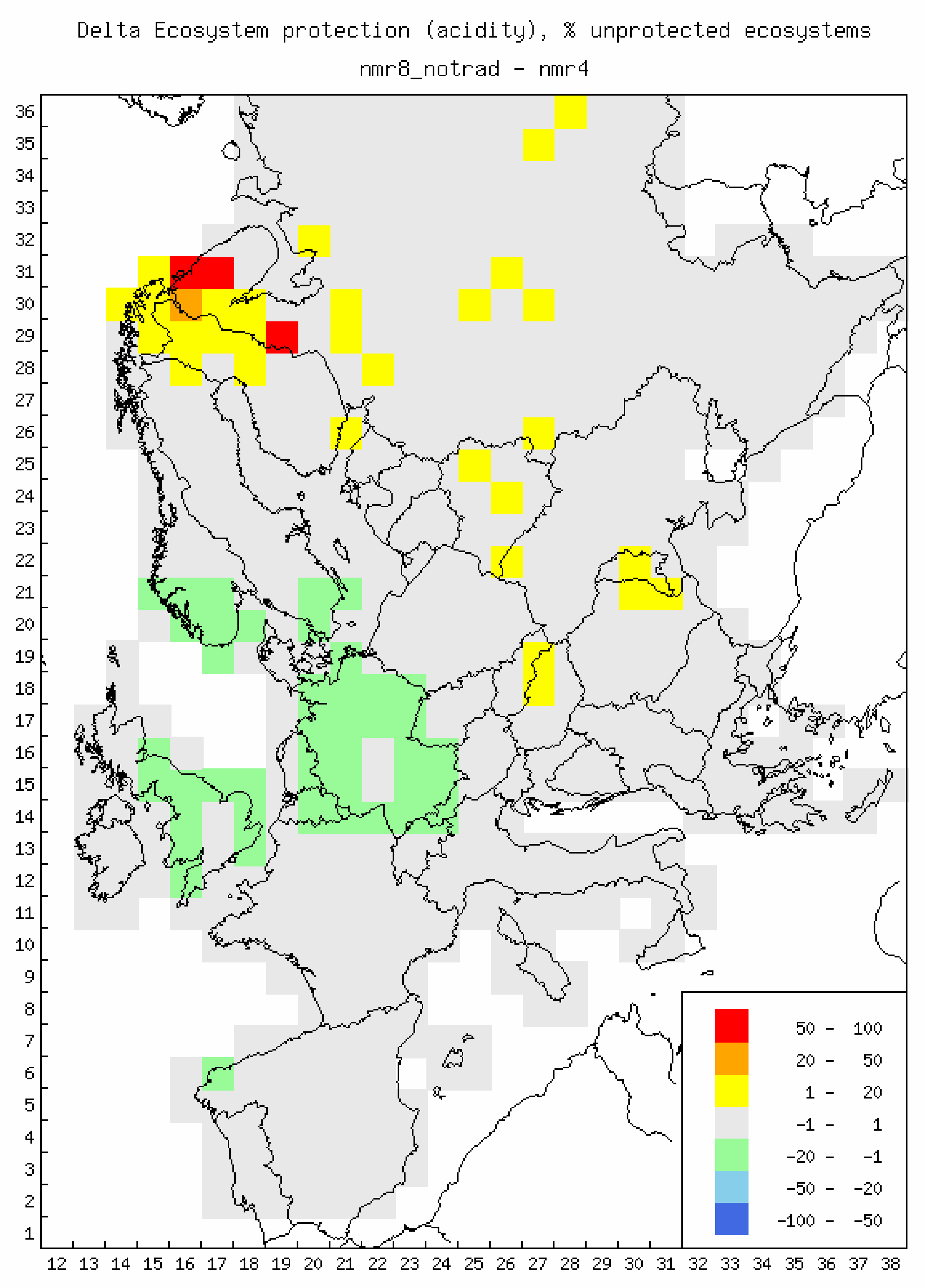
5
4
3
2
1
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
20.0 - 50.0
10.0 - 20.0
0.5 - 10.0
-0.5 - 0.5
-10.0 - -0.5
-20.0 - -10.0
-50.0 - -20.0


Delta Ecosystem protection (acidity), % unprotected ecosystems
nmr8_notrad - nmr4
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
50 - 100
20 - 50
1 - 20
-1 - 1
-20 - -1
-50 - -20
-100 - -50

3.3.2 Eutrophication

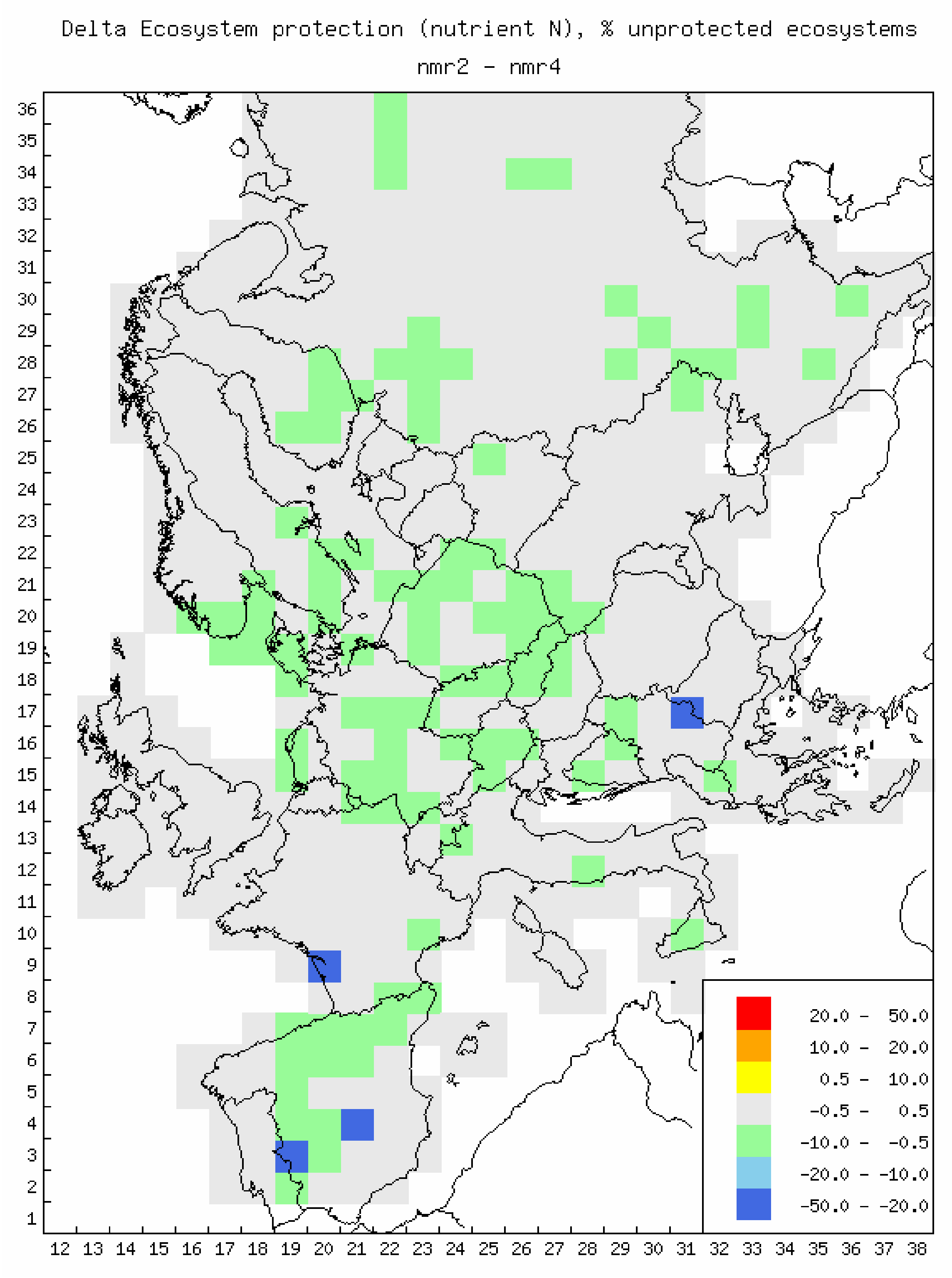
We are using changes in ecosystem protection (nutrient N) (% unprotected ecosystems) as an indicator for eutrophication. This is shown for selected scenarios in Figure 8.

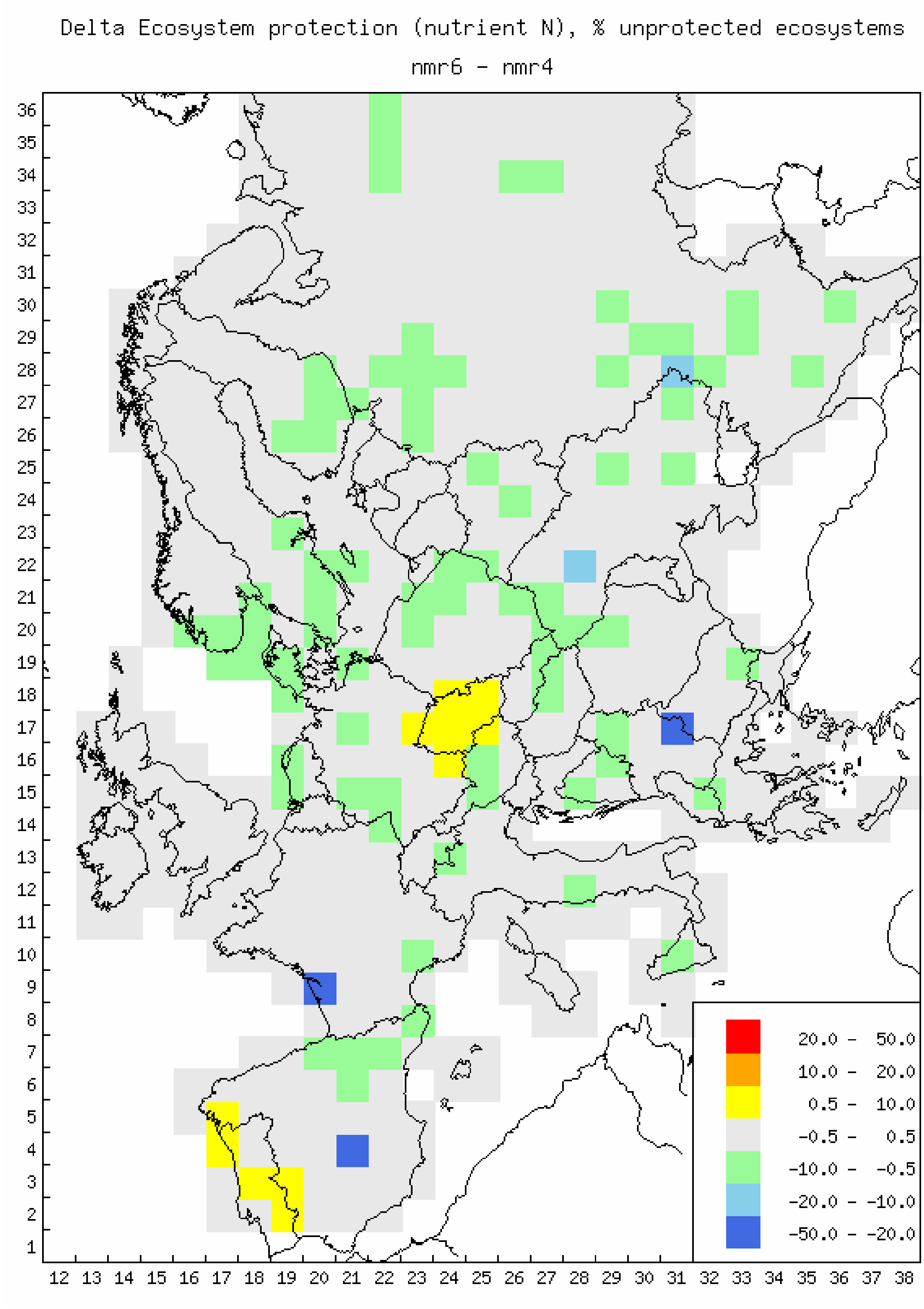
Further reductions in CO_2 emissions undertaken until 2020 will imply small (0-10 percentage points) reductions in unprotected ecosystems in large parts of Europe, including Spain, Germany Poland, Denmark, the southern part of Scandinavia and Russia. In a few grids the reductions exceed 20 percentage points. The largest relative changes in unprotected areas will be in the Nordic countries (southern part). However, the changes are smaller than for acidification.

The difference in effects between S4, S5, S6 and S7 (illustrating the effects of ETS expansion and taxes) is not large between these scenarios (as expected from the small changes in emissions). However, the per cent of unprotected ecosystems increases slightly when the number of sectors included in the ETS increases in EU-15, while in the Nordic countries a benefit is seen going from S5 (current ETS to expanded ETS) because of long-range transport. S7 (with tax) will imply a very small increase in the area of unprotected ecosystems compared to S2 in EU-15. Again, a decrease is seen in the Nordic countries.

Scenario 8 *without* trade will, compared to keeping emissions at the Kyoto level, increase the per cent of unprotected ecoystems in Russia and Eastern Europe in a few grids where the changes are large. The reductions in Western Europe that would be expected from the necessity to reduce CO_2 emissions domestically are small compared to the S2 scenario (following from small reductions in NOx emissions). However, the area of unprotected ecosystems will increase in southern Scandinavia. Overall the effect of European climate policy only and no trade is decreased eutrophication in the Nordic countries and a reduction for EU-15 and for Europe seen as a whole. Scenario 8 *with* trade will imply increased eutrophication in Europe, compared to S2, the effect will be close to S4 (less strict cap on GHG emissions).

Figure 8. Nutrient N: changes in ecosystem protection




Delta Ecosystem protection (nutrient N), % unprotected ecosystems
nmr6 - nmr4
36
35
34
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25
24
23
22
21
20
19
18
17
16
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10
9
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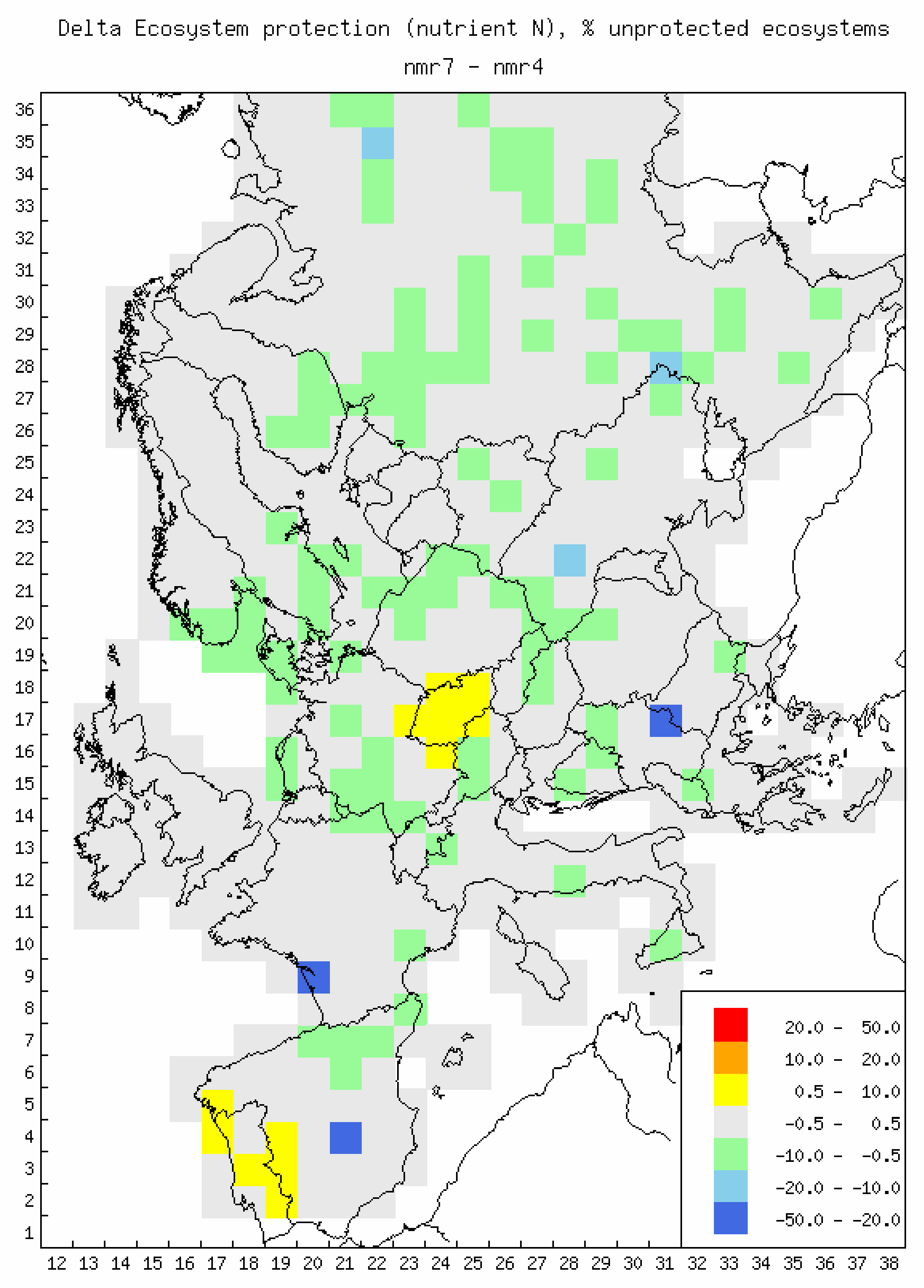
7
6
5
4
3
2
1
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
20.0 - 50.0
10.0 - 20.0
0.5 - 10.0
-0.5 - 0.5
-10.0 - -0.5
-20.0 - -10.0
-50.0 - -20.0


Delta Ecosystem protection (nutrient N), % unprotected ecosystems
nmr7 - nmr4
36
35
34
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25
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23
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20
19
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10
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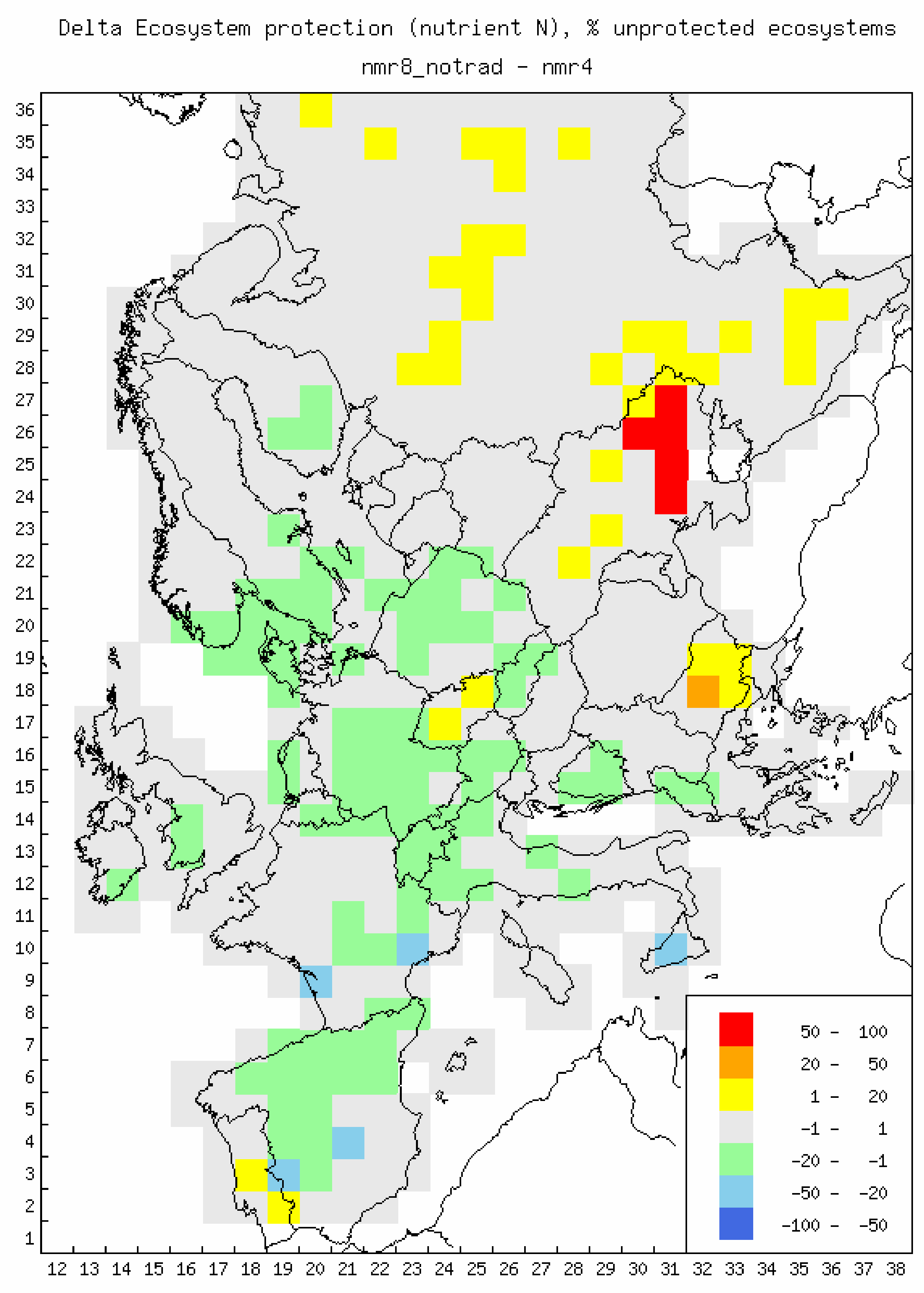
8
7
6
5
4
3
2
1
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
🟥 20.0 - 50.0
🟧 10.0 - 20.0
🟨 0.5 - 10.0
⬜ -0.5 - 0.5
🟩 -10.0 - -0.5
🟦 -20.0 - -10.0
🟦 -50.0 - -20.0


Delta Ecosystem protection (nutrient N), % unprotected ecosystems
nmr8_notrad - nmr4
36
35
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24
23
22
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11
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9
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7
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5
4
3
2
1
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
50 - 100
20 - 50
1 - 20
-1 - 1
-20 - -1
-50 - -20
-100 - -50

3.3.3 Ozone

Changes in AOT40[11] (excess ppm hours) has been used as an indicator for ozone.

A more ambitious climate policy (scenario 2 compared to scenario 4) will imply reductions in ppm hours exceedances in Europe, particularly in southern and central Europe and Russia, of -0.2-0.5. The effect for the Nordic countries is small in absolute terms since exceedances already are low here; the percentage reduction is 7 %.

ETS expansion implies that the excess ppm-hours is increasing slightly, but the effect for the Nordic countries is negligible. Increasing the number of sectors included in the ETS means fewer benefits in terms of ozone reductions in southern Europe in particular. Addition of a tax to non-ETS sectors (S7 over S4) implies a small increase in ppm-hours in Southern Europe, but no changes to the Nordic countries. The differences in effects of S4, S5, S6 and S7 (illustrating the effects of ETS expansion and taxes) are, however, not large.

The situation with Russian withdrawal from climate cooperation and no trade (S8NoT) will imply increases in excess ppm-hours over Russia and central Europe compared to S2. Reductions in southern Europe and the Nordic countries will be large. Because of the large reduction in Southern Europe, the overall effect of this scenario for Europe as a whole will not be much different from S2.

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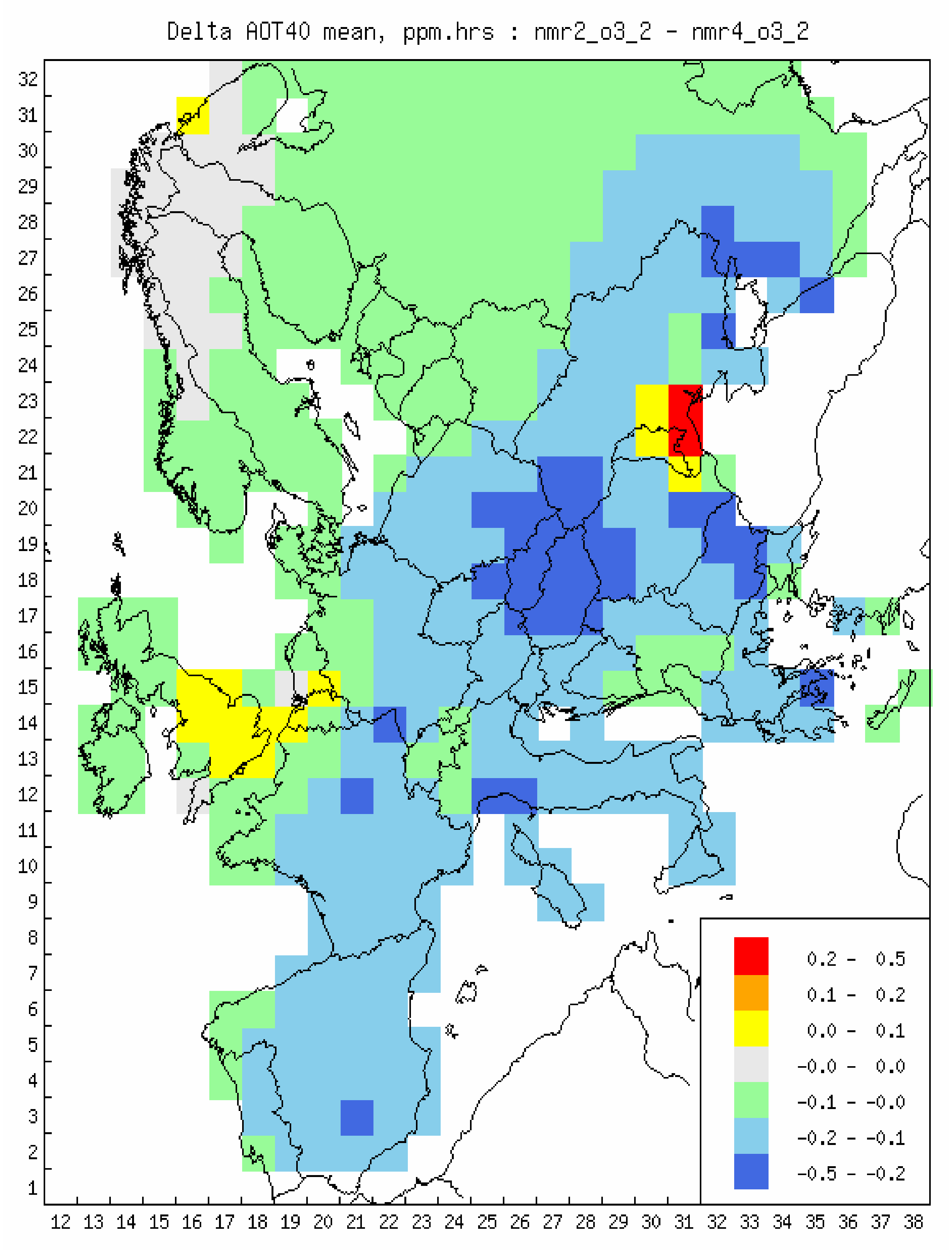
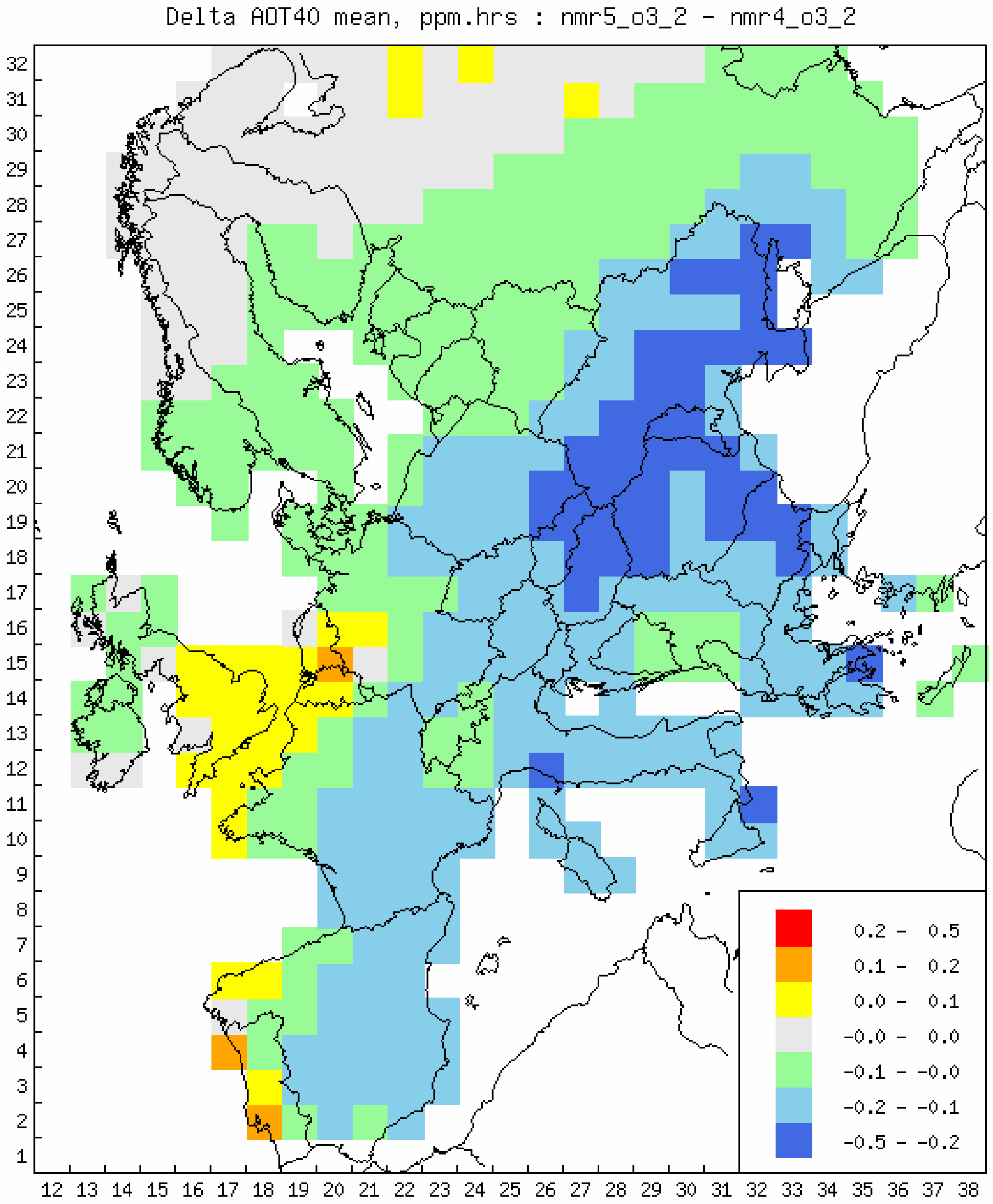
[11] AOT40 (Accumulated dose over a threshold of 40 ppb) is the sum of the differences between the hourly mean ozone concentration (in ppb) and 40 ppb for each hour when the concentration exceeds 40 ppb, accumulated during daylight hours. This indicator is often used for effects on crops and plants.

Figure 9. Ozone: Changes in AOT mean




Delta AOT40 mean, ppm.hrs : nmr5_o3_2 - nmr4_o3_2
32
31
30
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
14
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12
11
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6
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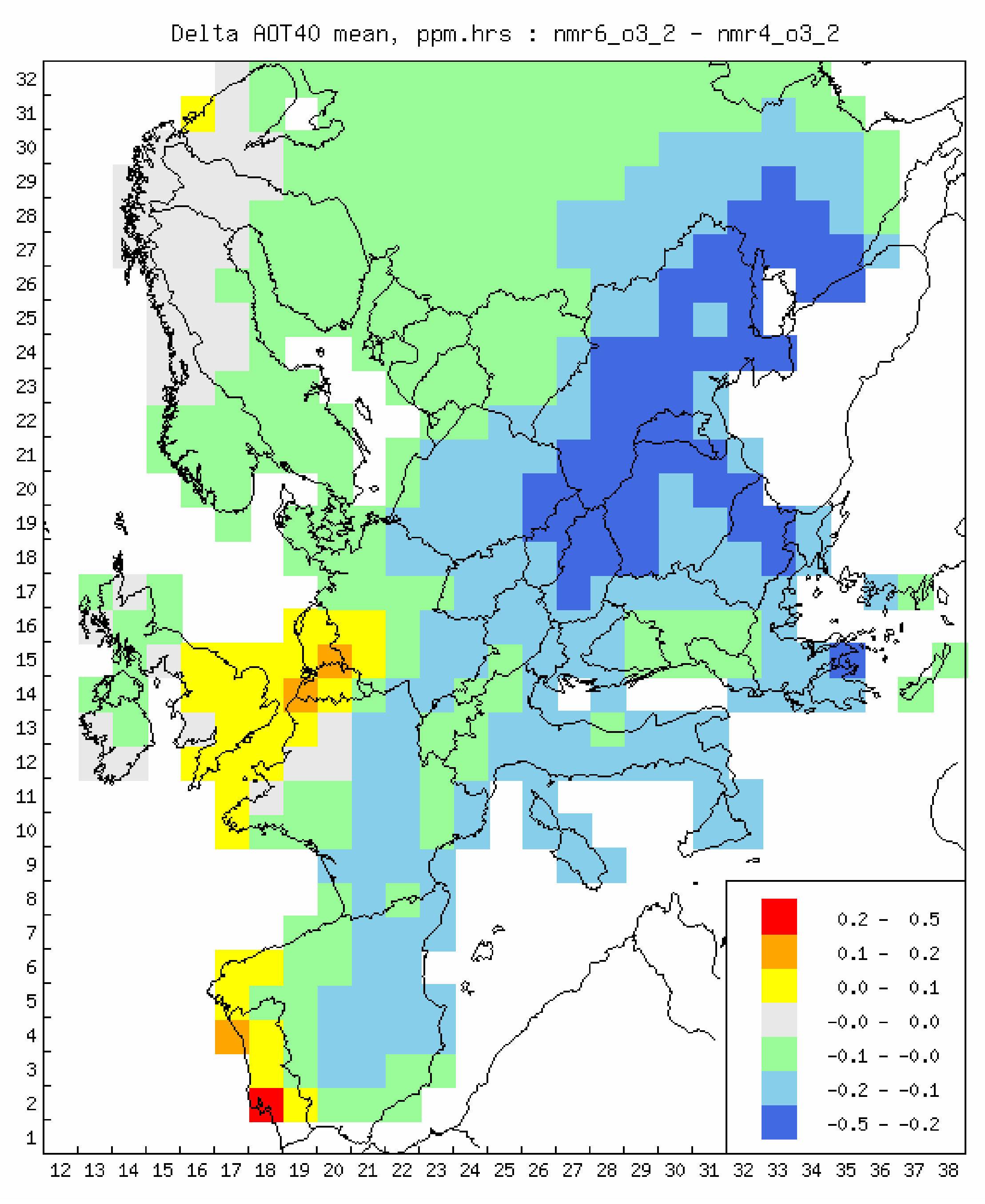
4
3
2
1
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
0.2 - 0.5
0.1 - 0.2
0.0 - 0.1
-0.0 - 0.0
-0.1 - -0.0
-0.2 - -0.1
-0.5 - -0.2


Delta AOT40 mean, ppm.hrs : nmr6_o3_2 - nmr4_o3_2
32
31
30
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23
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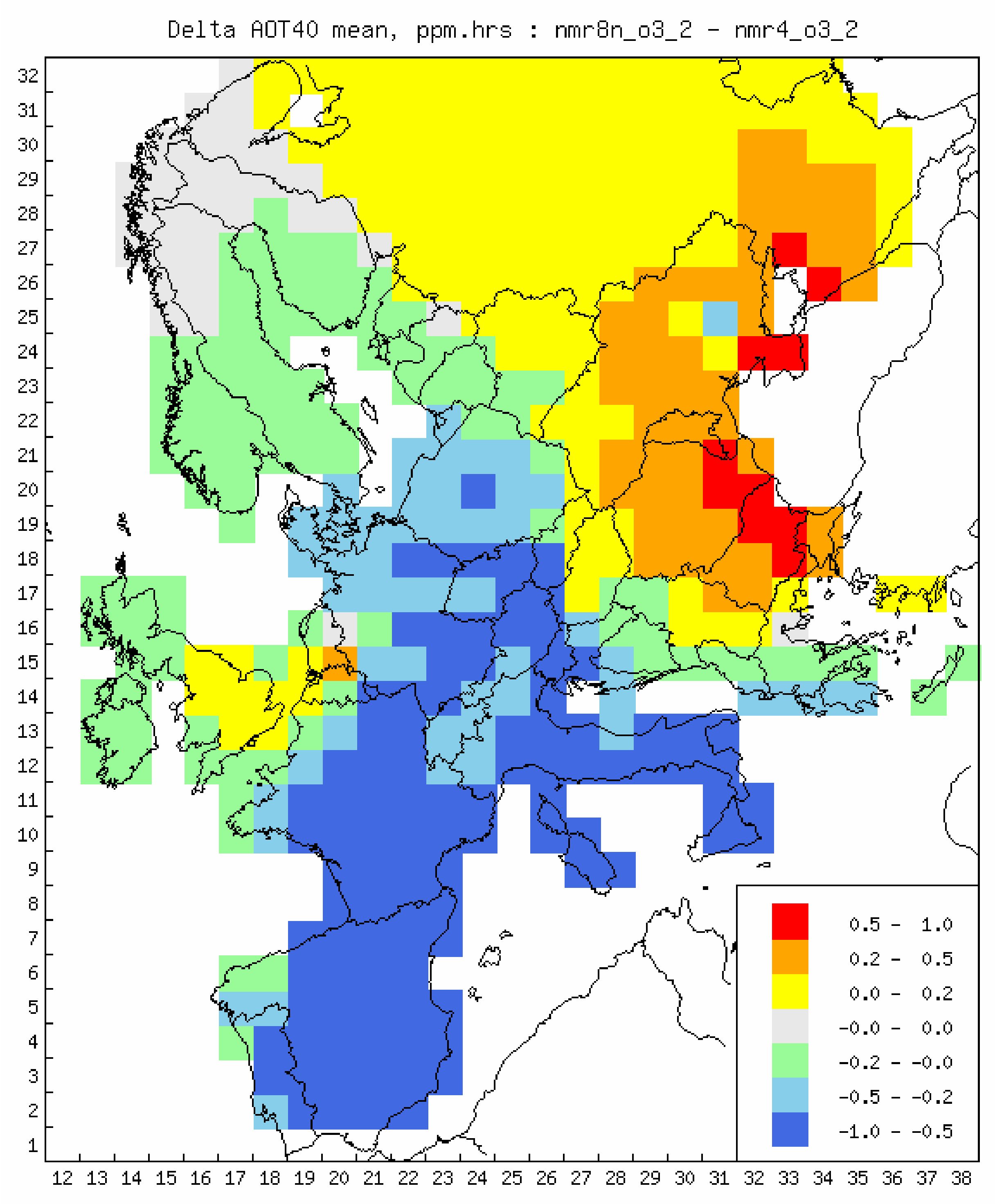
12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
0.2 - 0.5
0.1 - 0.2
0.0 - 0.1
-0.0 - 0.0
-0.1 - -0.0
-0.2 - -0.1
-0.5 - -0.2


Delta AOT40 mean, ppm.hrs : nmr8n_o3_2 - nmr4_o3_2
32
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23
22
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12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38
0.5 - 1.0
0.2 - 0.5
0.0 - 0.2
-0.0 - 0.0
-0.2 - -0.0
-0.5 - -0.2
-1.0 - -0.5

3.3.4 PM exposure

Figure 10 shows the contribution of primary $PM_{2.5}$ emissions from all European countries to annual average concentrations in year 2000 (Sofiev et al. 2006). In Finland their contribution is 1.2 to 2 $\mu g\ m^{-3}$ in southern Finland near the Helsinki region and below 1.2 $\mu g\ m^{-3}$ in the rest of the country. In this study, the possible changes in background concentrations from rest of Europe were not evaluated for 2020 or different scenarios. They would be somewhat lower in 2020, since the European emissions of primary PM will decrease in the future.

The concentrations caused by Finnish primary $PM_{2.5}$ emissions, without the contribution from other European countries, in 2000 and 2020 in the S2 scenario are presented in figures 11 a and b. Figure 11 c shows the population data. The concentrations decrease substantially from 2000 to 2020. It can be seen that the highest concentrations, mainly around 0.3 to 1 $\mu g\ m^{-3}$ in 2020, occur in southern Finland and near the Oulu region in central Finland, mainly in areas with high population densities or heavy industrial activities. With respect to their impact on health, these concentrations can be considered to be low.

The changes in population exposure in Finland due to Finnish emissions in 2000 and in different scenarios in relation to S4 are given in Figure 12. The relative changes of $PM_{2.5}$ emissions are given as well. The $PM_{2.5}$ emissions in 2000 are 19% higher than in 2020 in S2. As a result, population exposure is 27% higher. The change in population exposure is larger because the decrease in overall emissions between 2000 and 2020 happens mostly in traffic emissions that are concentrated near the highest population densities.

The differences in both Finnish emissions and exposure are relatively small between different scenarios in 2020. For example, traffic emissions are not much influenced by emission trading. A tighter post-Kyoto emission cap leads to a 4.5% reduction in emissions and population exposure. The lowest emissions and exposure are in scenario 8NoT, (Russian and Eastern Europe withdrawal, no trading).

The changes in emissions in different sectors have unequal impact on population exposure. In order to illustrate this, six additional scenarios were compiled, where 1000 tonnes of $PM_{2.5}$ were reduced in one sector at a time in each of the scenarios: (1) large power plants, (2) small power plants, (3) industrial processes, (4) domestic combustion, (5) road traffic, and (6) other sources. Figure 13 presents the relative changes in population exposure compared to S2, caused by the reduction of 1000 tonnes of $PM_{2.5}$ in these different sectors. Compared to other sources, the reduction in traffic emissions had the greatest impact on Finnish population exposure. The effect of reduced traffic is 20-64% larger than the other low emission altitude sources and 71-114% larger than due to the high emission altitude sources.

Figure 14 shows the respective changes from the reduction of 1000 tonnes of $PM_{2.5}$ on map for traffic, domestic combustion and large combustion plants. The spatial distribution of the relative decrease in exposure is different for different sectors. For traffic, the emission reduction of 1000 tonnes brings a 2-4% decrease in population exposure for the majority of the Finnish area. However, the decrease is higher, 4-8%, in areas with the highest concentrations and population densities. The respective reduction of domestic combustion emissions decreases the exposure by 3-4% in the majority of the grid cells, with lower fractions in densely populated areas where traffic or industrial activities dominate. The emission reductions in large sources decrease exposure by 1-3%, but exposure reductions up to more than 10% are estimated near the biggest polluters.

Figure 10. European background concentrations of $PM_{2.5}$ in 2000 (Sofiev et al., 2006)

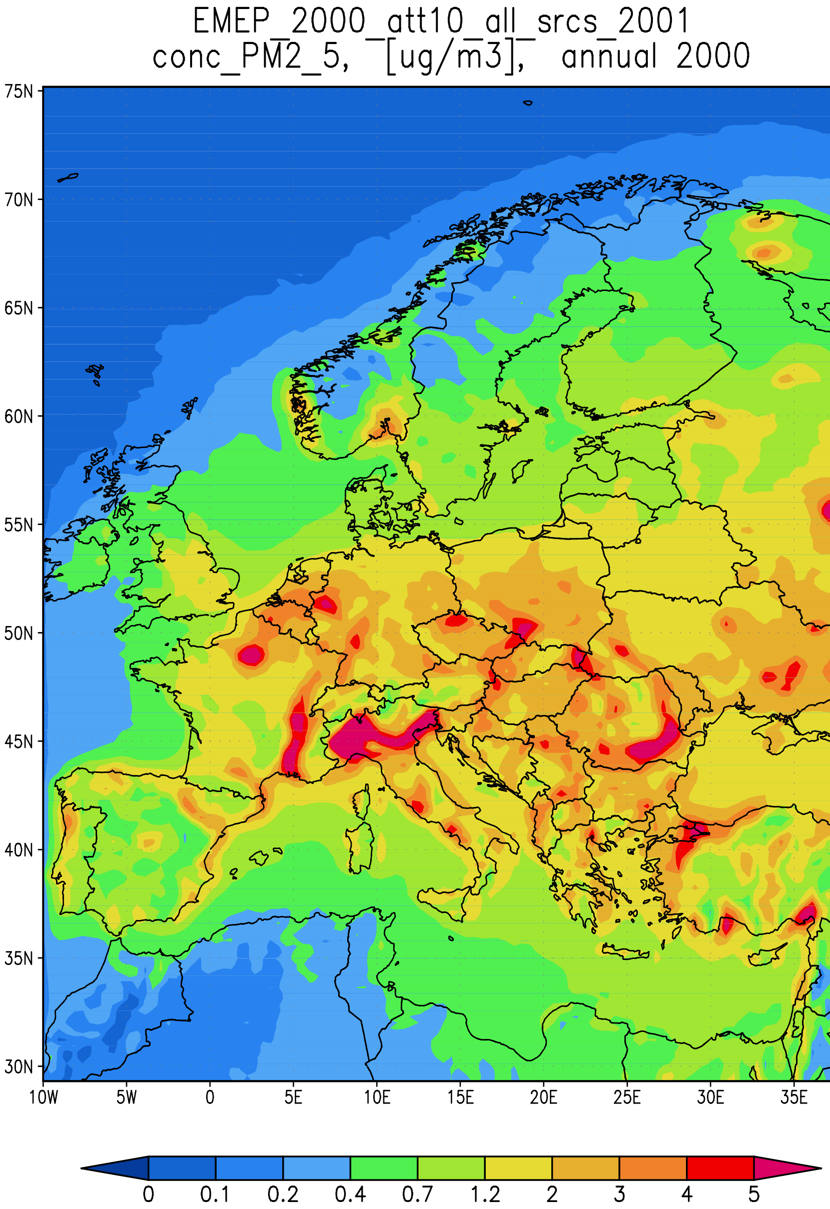


Figure 11. $PM_{2.5}$ concentrations caused by primary $PM_{2.5}$ from Finnish sources in (a) 2000 and (b) 2020 in S2. Population data is presented in (c)

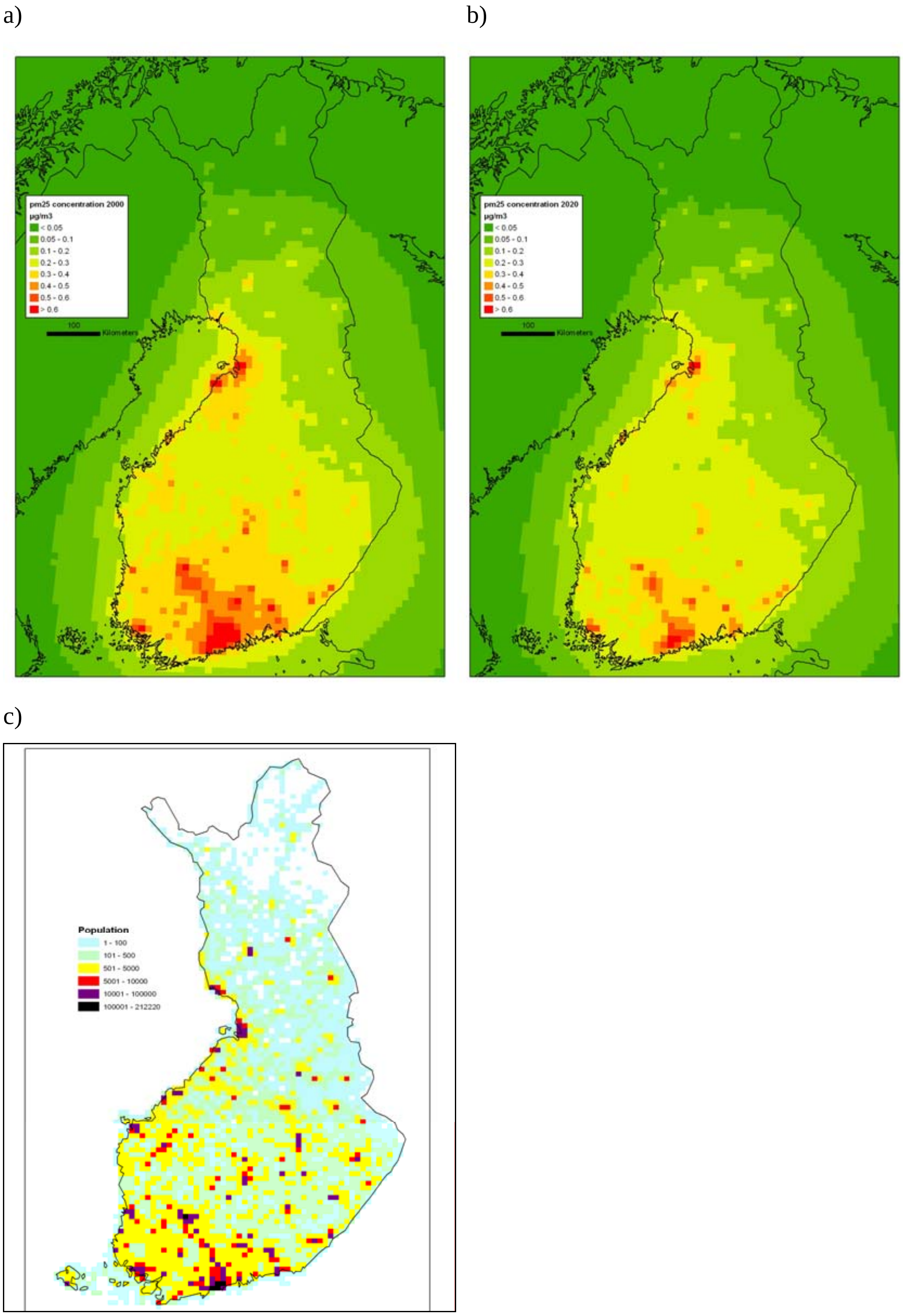


Figure 12. (a) Finnish primary $PM_{2.5}$ emissions and population exposure in Finland due to Finnish emissions in year 2000 compared to respective figures in 2020 in S4 scenario. (b) The changes in Finnish emissions and population exposure in different scenarios in 2020 compared to S4.

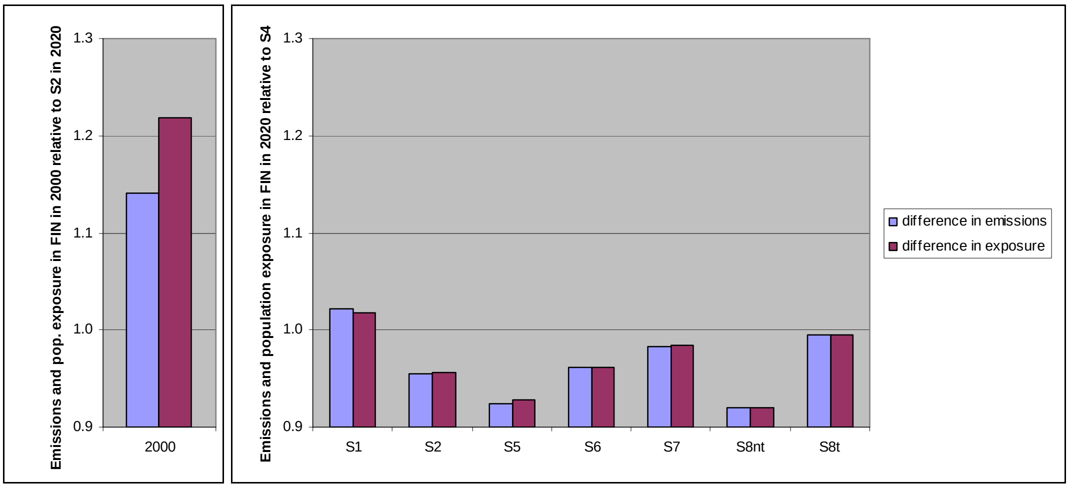

(a) (b)

Figure 13. Decrease in population exposure caused by the reduction of 1000 tonnes of $PM_{2.5}$ in (a) traffic, (b) domestic combustion and (c) large combustion sources

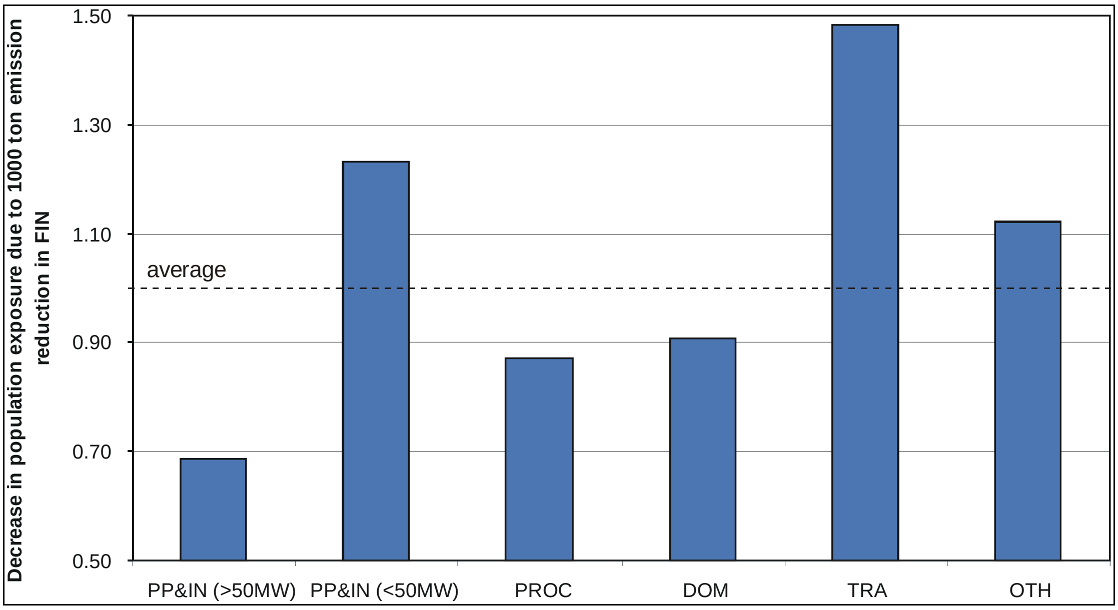
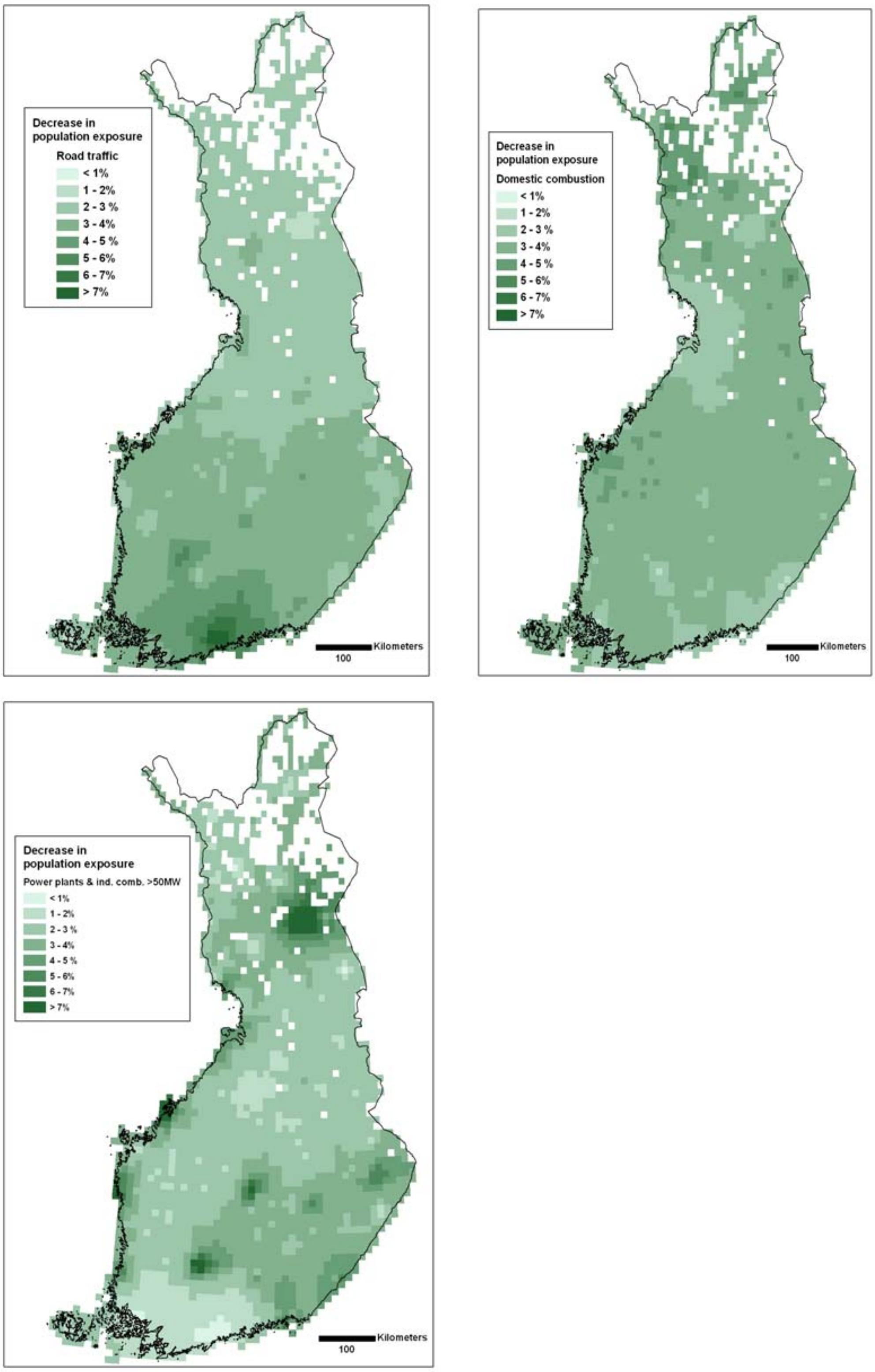


Figure 14. Decrease in population exposure caused by the reduction of 1000 tonnes of $PM_{2.5}$ in (a) traffic, (b) domestic combustion and (c) large combustion sources



4 Discussion

The benefits of CO_2 abatement through climate policies for air quality have been demonstrated in several studies. Syri et al. (2001) showed the synergies between climate policies and air pollution abatement. Van Vuuren et al. (2006) and EEA (2004) calculated the reduced costs required to meet targets for emissions of air pollutants in Europe due to climate policies until 2010. EEA (2006) has addressed the ancillary benefits up to 2030. Ancillary benefits of a more stringent EU climate policy will be greater by 2030 compared to 2020 because of the time required for restructuring the energy system (EEA, 2006). The report analyzes an EU GHG reduction target of 40% below 1990 levels by 2030. Benefits of climate policies are largest in New Member States and other Eastern European countries (EEA 2006).

In this study, the focus is on the post-Kyoto period 2010-2020. The climate policies for this period are as yet undetermined and we demonstrate how options for targets, inclusion of additional sectors in the emission trading scheme and trading between Russia/Eastern Europe and the rest of Europe affect emissions of air pollutants and air quality, with a main focus on the Nordic countries.

4.1 Emissions and environmental effects

The current study confirms that climate policies targeting CO_2 will have additional benefits in reduced emissions of air pollutants also until 2020. For the Nordic countries, this is most pronounced for SO_2 and particulate matter. For NO_x the differences between the ambition levels for post-Kyoto climate policies are slightly smaller. Furthermore, for SO_2 and NO_x the reduced emissions as a result of a more ambitious climate policy in the Nordic countries are smaller than in the rest of EU. We find that inclusion of the current European Annex I countries of the Kyoto Protocol in a post-Kyoto climate regime allowing emission trading implies a shift in CO_2 emissions between regions, which is in agreements with previous studies (Syri et al., 2001; van Vuuren et al., 2006). Less GHG reductions are achieved in countries that are buyers of permits. These shifts in CO_2 emissions will also imply a regional shift in emissions of SO_2, NO_x and particulate matter. The Nordic countries are typically expected to be buyers of permits, shifting emission reductions to Russia and Eastern Europe[12]. The effect on SO_2 (and PM) is the largest because fuel switching (for example from coal to gas) to a lesser extent will reduce NOx emissions.

The GHG emission targets after 2012 will influence the area of unprotected ecosystems in the Nordic countries. The benefits for ecosystems are largest for SO_2 and less for ozone and eutrophication. Effects on ozone and eutrophication are also determined by other pollutant emissions (e.g. NMVOC and NH_3, respectively) that are less influenced by climate policies (EEA, 2005; van Vuuren et al., 2006). The environmental benefits in the Nordic countries are larger than those obtained from the domestic reductions in emissions. This is because emission reductions in other regions, for example Russia will result in less long-range transport of air pollution to the Nordic countries. The reductions in PM emissions following different GHG emission targets will result in a reduced human exposure that is only slightly smaller in percentage terms than the reduction in domestic emissions.

Expanded ETS will result in small increased emissions of air pollutants because abatement is moved to sectors where CO_2 abatement is cheaper but less efficient in reducing air pollutants. The sector expansion is most important for SO_2 and PM, and less important for NO_x. The expansion of the current ETS to expanded ETS (adding chemicals and aluminium) is more important for increase in emissions of SO_2 and NO_x than the assumed extra sectors (machinery, other minerals, transport equipment and construction) joining in 2015. The extra

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[12] We have assumed no surplus allowances (“hot air”) post 2010.

sectors are also important for PM. The environmental effects of the expanded ETS are generally small.

The option of adding a carbon tax to households, transport and service sectors in 2015 leads to small increases in SO_2 emissions and has no or small effect on NO_x. This tax leads to an increase in PM emissions in the Nordic countries and rest of EU, in contrast to a decrease in the rest of Europe. The increase in emissions can be explained by a switch from fossil fuels to bio energy[13]. Acidification will increase slightly as a result of this tax.

In a situation where EU (including Norway) collaborates in reducing GHG emissions post 2012 and Russia and Eastern Europe do not, higher reductions in GHG emissions would be necessary in Western Europe. If trading is not allowed between regions, carbon leakage would result. For SO_2 this scenario overall gives the highest emissions (apart from no climate policy), while for the Nordic countries and EU-15 the scenario with trade results in the highest emissions, as it will result in fewer domestic measures to reach the same target. For NOx and PM, the scenario with trade results in the overall highest emissions. The scenario without trade will generally imply an increased impact on ecosystems in Russia and Eastern Europe and improvements in Western Europe. However, the area of unprotected ecosystems for acidification will increase in northern Scandinavia, and the area of unprotected ecosystems for eutrophication would increase in southern Scandinavia. The reason is that reduced emissions in Russian and Eastern Europe may indirectly result in environmental benefits in Western Europe (van Vuuren et al., 2006). Ozone will increase in Eastern Europe and be reduced in the Nordic countries. The scenario of Russian and Eastern European withdrawal with trade allowed will result in increased acidification and eutrophication in the Nordic countries compared to a situation with targets in all European countries.

Table 9 provides an overview of how the Nordic countries are influenced by the various options for climate policies.

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[13] The impact of a carbon tax on the transport sector may be underestimated since there are little if any substitution opportunities for switching away from oil in transport in GRACE. In some cases, some substitution is unavailable because sectors that do not use a given input in the base year (i.e. gas) are not allowed to start using that good in subsequent years. This is because of the way the production structure is calibrated in GRACE (and other CGE models). As a consequence, any abatement in the transport sector will be much more expensive than in other sectors, and it thus makes only a limited contribution to abatement in each regions - in spite of actually contributing around 20% of regional emissions. This is an artifact which is not trivial to fix.

Table 9. Influence of options for post-2012 climate policies on emissions, costs and effects on the Nordic countries (% difference between scenarios in 2020 unless specified)

	Tighter cap on emissions in the post-Kyoto period (S4 to S2)	ETS expansion (from current to expanded ETS with extra sectors (S5 to S6))	Russian & Eastern Europe withdrawal -without allowing trade (S2 to S8 NoT)	Russian & Eastern Europe withdrawal -allowing trade (S2 to S8T)
Emissions				
- CO_2	-5.3	+2.4	-14.9	+7.2
- SO_2	-2.5	-	-12.1	+2.5
- NO_x	-2.0	+0.5	-6.9	+2.1
- $PM_{2.5}$	-3.4	+2.7	-16.8	+3.6
Effects				
- Acidification	-11.1	+1.3	+25	+13
- Eutrophication	-5.2	-0.9	-6.0	+6.8
- Ozone	-7.3	+0.0	-15.8	-
- PM population exposure (Finland)*	-4.4	+4.1	-	+4.0
Alternative costs of reducing air pollutants with technical measures [Million€]	7	-9*	182	-7
Welfare change	-0.6	+0.4	-2.6	+0.7

* Only exposure caused by Finnish primary $PM_{2.5}$ emissions (changes - 4.5, + 4.3, - , + 4.2, respectively) considered

4.2 Avoided costs and welfare changes

The avoided costs associated with different CO_2 abatement scenarios show how much effort would be required if the scenario-specific environmental co-benefits were desired, but by still holding the energy system fixed (not reducing any CO_2 emissions). The avoided costs can serve as an indication of co-benefits from the CO_2 abatement strategies. One can regard the alternative cost estimations as a value of co-benefit of CO_2 abatement. Another interesting aspect is the distribution effect of the different strategies. This could be important from a political perspective as yet another input in the international burden sharing when discussing emission reductions and other abatement options. For the Nordic countries a tighter cap on emissions in the Post-Kyoto Period would imply that costs are moved to abating CO_2 and 7 million Euros are saved on abating air pollutants. Expansion of the ETS will imply additional costs of abating air pollutants of 9 million Euros compared to keeping the ETS inclusion at the current level. Russian and Eastern Europe withdrawal from the climate regime with trade allowed will imply a cost of additional abatement of the same magnitude. If trade is not allowed, the large domestic efforts for GHG abatement would mean that large costs are saved in air pollution end-of-pipe measures. The regions “Nordic countries” and “Rest of EU-25” are always subject to smaller changes in welfare than the regions “Poland & Baltic States” and “Rest of Europe & Russia”. These relatively modest welfare changes in the Nordic countries partly are an effect of how the energy system is constructed in these regions. The carbon intensity in the energy system affects how sensitive the region is to different ETS and emission cap ambition levels.

Using the concept of avoided costs for estimating co-benefits is sensitive to redistribution effects. High avoided costs might be an effect from large air pollutant removals overall, as is the case when studying the effect of a tighter cap on post-Kyoto CO_2 emissions (S2 to S4). Correspondingly, negative or low avoided cost is an indication of CO_2 abatement without full synergy effects on air pollutant abatement (S5 to S6 gives higher SO_2 and lower NO_x emissions). But it might also be the effect of a redistribution of CO_2 abatement efforts as is the case when the studying the effect of a withdrawal of East Europe and Russia (S2 to S8NoT). A maximum synergy effect is illustrated by low unit alternative costs for air pollutant abatement in combination with high total air pollutant emission removal. A comparison of the scenarios for all Europe can be seen in table 10.

Table 10. Unit avoided costs on top of S4, Europe 2020 (average costs)

Scenario	**Per air pollutant abated**		
	SO_2 [€ / tonne]	**NO_x [€ / tonne]**	**$PM_{2.5}$ [€ / tonne]**
S1	0	-4	0
S2	335	269	109
S5	416	237	148
S6	334	217	108
S7	565	248	112
S8NoT	5790	-561	52150
S8T	0	0	0

For NO_x, SO_2 and PM altogether, the most effective abatement strategy seen for Europe as a whole would be S6, despite that S5 reduces more SO_2. This is partly because of the steep cost curves for air pollution abatement, and partly because of the fact that NO_x and PM abatement is focused in the region “Rest of Europe and Russia” in S6 where technical abatement costs are lower. It is also worth noting that the welfare loss is the smallest for S6, and it has also the most equal emission abatement distribution over the countries. The expansion of the ETS implies a small positive welfare change, because abatement is implemented in more sectors allowing for inclusion of a wider range of low cost abatement options. However, an abatement strategy may need to weight the decision of abating SO_2 against NO_x and PM. Again it must be stressed that these unit costs are underestimations due to reasons mentioned earlier.

4.3 PM abatement and human exposure

When considering sectoral PM emissions in Finland, the biggest variation in emissions between the scenarios is the residential combustion sector. Domestic wood combustion entails relatively high emission factors, and the wood combustion volumes may differ in different scenarios depending on e.g. the assumptions of renewable energy support. However, it is important to bear in mind that a higher share of bio energy can be introduced combined with low-emitting stoves. The changes in large industrial and power plants are relatively small. They use efficient control measures and emissions are low regardless of energy production method. Also traffic exhaust emissions are low in 2020, and traffic volumes do not differ much between different scenarios. We assume that the development of sectoral emissions in the other Nordic countries in different scenarios is mainly similar to Finland.

The effects of $PM_{2.5}$ emissions on human health entail, in addition to long-range transboundary aspects, also more local aspects that depend on the location and altitude of emissions in relation to the location of population. Therefore, national PM modelling studies with a fine spatial resolution supplement the information obtained from international models, such as RAINS. Naturally, the relationship of the spatial distribution of sectoral emissions and population is different in different countries. However, the following generalizations from the Finnish case study for the other Nordic countries can be made:

- The decrease/increase in the emissions from the traffic sources has a relatively bigger effect on population exposure than other sectors. This is because traffic emissions occur mainly in urban and other densely populated areas. This study suggests that the reduction of the same mass of traffic emissions in Finland decrease Finnish population exposure by 20-114% compared to those of other emission sources. A study at 1×1 km^2 spatial resolution by Tuomisto et al. (submitted) suggests that the differences in emission–exposure relationship between traffic and domestic combustion might be even larger than what was perceived in this study. The respective differences are presumably of the same order of magnitude in the other Nordic countries.
- The emissions of domestic wood combustion mainly take place in rural and other relatively sparsely populated areas. Therefore, their effect on population exposure on average is not as large as that of e.g. traffic. However, there are considerable domestic wood combustion activities also in more densely populated residential areas of medium-sized cities, and also in major Nordic cities (e.g. Oslo). As a renewable energy source with increasing popularity, the PM emissions of domestic wood combustion should be considered carefully.
- High stack emissions from large power plants and industrial processes have considerably lower population exposure effects than low altitude sources.

4.4 Uncertain future

This study has illustrated how uncertainties in post 2020 climate policies influence our ability to predict emissions, effects and costs. The most influential element of uncertainty in post-2012 emission scenarios of air pollutants is the level of future climate commitments in the EU and engagements in climate policies in Russia and Eastern Europe. Inclusion of additional sectors has only a small effect. There are evidently also other unknown factors that could change the conclusions of this study, such as energy prices and emphasis of non-energy abatement options.

In our analysis, fuel prices are relatively stable for the model period 2000-2020, with only climate policy generating the price shock to induce fuel switching. Thus, in our no-policy scenario, the fuel mix is broadly the same over the model period. However, in the real world, fuel prices are affected by numerous factors (weather, geopolitics, speculation, developing country demand, etc.) beyond the scope of climate policy. If we assume that a price shock of, for example, increased oil and gas prices occurs over the period 2000-2020, and that they cause fuel substitution towards cheaper coal, we would find that the fuel mix is significantly different in 2020 compared to 2000. Under a no-policy trajectory with higher coal shares than the 2000 levels, the co-benefits of carbon abatement would be larger than a trajectory with e.g. higher oil and gas shares. This is a result of the higher SO_2 and PM emissions from coal than gas. On the other hand, it is possible that a real-world price shock of increased oil and gas prices occurs (as has been the case for the period 2000-2006), and yet the expected levels of fuel switching do not follow. This would likely be a consequence of short vs. long-term views of fuel prices and switching. Industry and consumers may expect high oil prices (caused by weather or geopolitics) to be a short-term phenomenon and be unwilling to replace their capital stock for alternative fuel use. Climate policy, if considered a long-term phenomenon, may cause substitution through price shocks, but the “power” (marginal increase to the fuel unit cost) of the carbon taxes or permit prices will be much smaller under a high background oil price compared to a lower oil price. As a consequence, equivalent targets would require a higher carbon price, and abatement may be distributed towards non-oil/gas fuels (that do not have the price shock). It is difficult to predict how this will affect the co-benefits of climate policy in absolute terms; however, we can expect that the general patterns and directions we see in our scenarios would hold. Our modelling framework does not allow us to address the short-term vs. near-term dichotomy of price expectations, and thus we simply have immediate substitution away from a given fuel source. With improved dynamics and investment treatment, issues related to uncertainties in fuel prices could be better examined in GRACE.

Capture and storage of CO_2 is a measure to reduce CO_2 released to the atmosphere that may become important in the post-Kyoto period. This measure has not been included in this study, and if implemented may lead to different conclusions about co-benefits of climate policies. In particular this option must be considered for stricter targets than included in this study. We have considered only CO_2 and not other Kyoto gases. The considerations for co-benefits may be different if non-CO_2 gases were included. Depending on mitigation costs, including these gases may result in preference for mitigation options which have less synergies in reducing air pollutants emissions than for example fuel switch and energy efficiency improvements.

5 Conclusion

Stricter commitments for GHG emissions in the post-Kyoto period until 2020 will contribute to reducing emissions of air pollutants (SO_2, NO_x and particulate matter) in the Nordic countries, reduced costs for end-of-pipe abatement to reach a specific target for air pollutant emissions and benefits in terms of reduced acidification, eutrophication, ozone effects on crops and human exposure to particulate matter. However, the reductions in emissions in the Nordic countries are smaller than in other regions since anticipated use of the flexible mechanisms implies a shift in GHG abatement, and co-benefits, to other regions – in particular Russia and Eastern Europe. On the other hand, the Nordic countries benefit from reductions in emissions in other regions due to reduced long-range transboundary air pollution. Expanding the greenhouse gas emission trading scheme to include additional sectors will imply increased air pollutants emissions and a slight worsening of the environment, but the welfare effects are positive due to lower costs of CO_2 abatement, and for Europe as a whole this would imply reduced costs. If the EU and Norway are involved in a climate policy cooperation that excludes other regions, this will imply that more greenhouse gas emission reductions are undertaken in the Nordic countries with entailed reductions in air pollutant emissions. This would benefit ecosystems in southern Scandinavia, but acidification would increase in the north because of increased emissions in Russia. These reductions would also have large negative welfare effects because CO_2 abatement is more expensive. For human exposure to $PM_{2.5}$, road transport is particularly important and this source is less influenced by the options for climate policies. The Nordic countries burn a lot of wood as domestic fuel, which may increase if a fuel tax is put on sectors not included in the emission trading scheme and result in increased PM emissions. As long as post-Kyoto climate policies are unknown, there are therefore large uncertainties about the required costs of achieving a different level of air pollutant emissions, ecosystem protection and human exposure in 2020. A large part of this uncertainty comes from the degree of Russian and Eastern Europe climate policy cooperation.

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7 Annex 1. Technical description of conversion of GRACE results into RAINS input, including treatment of New Technologies in the RAINS energy sector

7.1 Conversion of GRACE results to RAINS activity data.

The conversion of GRACE results into RAINS activity data is performed so that the scenarios examined in GRACE can be explored in RAINS for the calculation of SO_2 and NO_x emissions.

The activities in all RAINS sectors, countries and years (*A*) are calculated as the product of initial activity levels (*IA*) in RAINS for the year 2000 and the indexed growth value for the related sectors in GRACE (I) for the chosen year.

$$A_{i,\, s,\, f,\, y} = IA_{i,\, s,\, f,\, 2000} * I_{j,\, s',\, f',\, y} \qquad \text{Equation A1}$$

where:

i, s, f, y = Country, RAINS sector, RAINS fuel, year (2005, 2010, 2015, 2020)
j, s', f', y = GRACE region, GRACE sector, GRACE fuel, year (2005, 2010, 2015, 2020)

In the conversion process, the determining factors are as follows: the part of the GRACE economy to which the RAINS sector should be regarded as belonging; which fuels in GRACE that are concerned; and finally, which GRACE sector corresponds to the RAINS sector in question. The RAINS sectors are allocated to the corresponding GRACE sectors, fuels/drivers and structure according to the following list:

Table A1. Corresponding RAINS and GRACE sectors.

RAINS activity type:	RAINS sector	GRACE sector	GRACE Energy / Driver
Process and other activities		GRACE structure: Domestic Output, Aggregate energy demand in processes, Population growth	
	CRU-PROD-[PJ]	CRU	OUT
	GAS-PROD-[PJ]	GASPROD	OUT
	GAS-TRANS-[PJ]	GAS	OUT
	NOF-ALU_PFPB-[Mt_prim_Al_prod/year]	NFM	OUT
	NOF-ALU_SWPB-[Mt_prim_Al_prod/year]	NFM	OUT
	NOF-CONSTRUCT-[M_m2]	CNS	OUT
	NOF-MAGNPR-[t_Mg_processed/year]	NFM	OUT
	NOF-MINE_BC-[Mt]	OMN	OUT
	NOF-MINE_HC-[Mt]	OMN	OUT
	NOF-OTHER_NOX-[kt]	OMF	OUT
	NOF-OTHER_PM-[kt]	OMF	OUT
	NOF-OTHER_SO2-[kt]	OMF	OUT
	NOF-PR_ADIP-[Mt]	CRP	OUT
	NOF-PR_ALPRIM-[Mt]	NFM	OUT

	NOF-PR_ALSEC-[Mt]	NFM	OUT
	NOF-PR_BAOX-[Mt]	I_S	OUT
	NOF-PR_BRIQ-[Mt]	COL	OUT
	NOF-PR_CAST-[Mt]	I_S	OUT
	NOF-PR_CAST_F-[Mt]	I_S	OUT
	NOF-PR_CBLACK-[Mt]	OIL	OUT
	NOF-PR_CEM-[Mt]	NMM	OUT
	NOF-PR_COKE-[Mt]	COL	OUT
	NOF-PR_EARC-[Mt]	I_S	OUT
	NOF-PR_GLASS-[Mt]	NMM	OUT
	NOF-PR_LIME-[Mt]	NMM	OUT
	NOF-PR_NIAC-[Mt]	CRP	OUT
	NOF-PR_OTHER-[Mt]	NMM	OUT
	NOF-PR_OT_NFME-[Mt]	NFM	OUT
	NOF-PR_PIGI-[Mt]	I_S	OUT
	NOF-PR_PIGI_F-[Mt]	I_S	OUT
	NOF-PR_PULP-[Mt]	PPP	OUT
	NOF-PR_REF-[Mt]	OIL	OUT
	NOF-PR_SINT-[Mt]	I_S	OUT
	NOF-PR_SINT_F-[Mt]	I_S	OUT
	NOF-PR_SMIND_F-[M_persons]	POP	OUT
	NOF-PR_SUAC-[Mt]	CRP	OUT
	NOF-RES_BBQ-[M_persons]	POP	OUT
	NOF-RES_CIGAR-[M_persons]	POP	OUT
	NOF-RES_FIREW-[M_persons]	POP	OUT
	NOF-STH_AGR-[Mt]	AGR	OUT
	NOF-STH_COAL-[Mt]	COL	OUT
	NOF-STH_FEORE-[Mt]	I_S	OUT
	NOF-STH_NPK-[Mt]	AGR	OUT
	NOF-STH_OTH_IN-[Mt]	NMM	OUT
	NOF-WASTE_FLR-[PJ]	OIL	OUT
	NOF-WASTE_ORG-[kt]	SER	OUT
	NOF-WASTE_PAP-[kt]	PPP Paper use in residential	OUT
	NOF-WASTE_RES-[Mt]	POP	OUT
	POP-WASTE_SEW-[mln_POP]	POP	OUT
	NOF-MINE_OTH-[Mt]	OMN	OUT
	NOF-WASTE_AGR-[Mt]	AGR	OUT
	NOF-PR_HEARTH-[Mt]	I_S	OUT
	NOF-ALU_VSS-[Mt_prim_Al_prod/year]	NFM	OUT
	NOF-PR_PELL-[Mt]	LUM	OUT
	NOF-ALU_VSS-[Mt prim Al prod/year]	NFM	OUT
Energy and Mobile sector		GRACE Structure: Intermediate Energy Demand, Intermediate Capital Demand, Final Household Energy Demand, Domestic Output,	
	BC1-IN_BO	TRN, OME, OMN, FPR, LUM, CNS, TWL, OMF, AGR	COL
	BC1-DOM	PRI	COL
	BC1-PP_EX_OTH	ELY	COL
	HC1-CON_LOSS	COL	OUT

	HC1-IN_BO	TRN, OME, OMN, FPR, LUM, CNS, TWL, OMF, AGR	COL
	HC1-IN_OCTOT	I_S, CRP, NFM, NMM, PPP	COL
	HC1-DOM	PRI	COL
	HC1-TRA_OT	T_T	COL
	HC1-PP_EX_OTH	ELY	COL
	HC1-NONEN	CRP	COL
	DC-IN_OCTOT	I_S, CRP, NFM, NMM, PPP	COL
	DC-DOM	PRI	COL
	DC-NONEN	CRP	COL
	OS1-CON_LOSS	ELY	OUT
	OS1-IN_BO	PPP	CAP
	OS1-IN_OCTOT	PPP	CAP
	OS1-DOM	PRI	ELY
	OS1-PP_EX_OTH	ELY	CAP
	OS1-PP_NEW	ELY	CAP
	OS2-IN_OCTOT	NMM	CAP
	OS2-PP_EX_OTH	ELY	CAP
	OS2-PP_NEW	ELY	CAP
	HF-CON_COMB	OIL	OUT
	HF-CON_LOSS	OIL	OUT
	HF-IN_BO	TRN, OME, OMN, FPR, LUM, CNS, TWL, OMF, AGR	OIL
	HF-IN_OCTOT	I_S, CRP, NFM, NMM, PPP	OIL
	HF-DOM	PRI	OIL
	HF-PP_EX_OTH	ELY	OIL
	HF-NONEN	CRP	OIL
	MD-IN_BO	All	OIL
	MD-DOM	PRI	OIL
	MD-TRA_RD	T_T	OIL
	MD-TRA_OT	T_T	OIL
	MD-PP_EX_OTH	ELY	OIL
	MD-PP_NEW	ELY	OIL
	GSL-DOM	PRI	OIL
	GSL-TRA_RD	T_T	OIL
	GSL-TRA_OT	T_T	OIL
	LPG-CON_COMB	GAS	OUT
	LPG-DOM	PRI	GAS
	LPG-TRA_RD	T_T	GAS
	GAS-CON_COMB	GAS	OUT
	GAS-CON_LOSS	GAS	OUT
	GAS-IN_BO	TRN, OME, OMN, FPR, LUM, CNS, TWL, OMF, AGR	GAS
	GAS-IN_OCTOT	I_S, CRP, NFM, NMM, PPP	GAS
	GAS-DOM	PRI	GAS
	GAS-PP_EX_OTH	ELY	GAS

	GAS-PP_NEW	ELY	GAS
	GAS-NONEN	CRP	GAS
	REN-DOM	PRI	ELY
	REN-PP_TOTAL	ELY	CAP
	HYD-PP_TOTAL	ELY	CAP
	ELE-CON_LOSS	ELY	OUT
	ELE-IN_OCTOT	I_S, CRP, NFM, NMM, PPP	ELY
	ELE-DOM	PRI	ELY
	ELE-TRA_OT	T_T	ELY
	ELE-PP_TOTAL	ELY	OUT
	HT-CON_LOSS	ELY	OUT
	HT-IN_BO	TRN, OME, OMN, FPR, LUM, CNS, TWL, OMF, AGR	ELY
	HT-IN_OCTOT	I_S, CRP, NFM, NMM, PPP	ELY
	HT-DOM	PRI	ELY
	HT-PP_TOTAL	ELY	OUT
	BC1-IN_OCTOT	I_S, CRP, NFM, NMM, PPP	COL
	HF-TRA_OTS	T_T	OIL
	MD-CON_COMB	OIL	OUT
	MD-IN_OCTOT	NMM	OIL
	MD-TRA_OTS	T_T	OIL
	GSL-NONEN	CRP	OIL
	LPG-NONEN	CRP	GAS
	NUC-PP_TOTAL	ELY	CAP
	BC1-CON_COMB	COL	OUT
	OS2-IN_BO	All except NMM	CAP
	LPG-IN_OCTOT	CPR	GAS
	HC1-CON_COMB	COL	OUT
	MD-NONEN	CRP	OIL
	GSL-CON_COMB	OIL	OUT
	GAS-TRA_RD	T_T	GAS
	HF-PP_NEW	ELY	OIL
	GSL-IN_OCTOT	CNS	GAS
	BC1-NONEN	CRP	COL
	DC-CON_COMB	COL	OUT
	BC1-PP_NEW	ELY	COL
	BC2-CON_COMB	COL	OUT
	BC2-IN_BO	TRN, OME, OMN, FPR, LUM, CNS, TWL, OMF, AGR	COL
	BC2-DOM	PRI	COL
	BC2-PP_EX_OTH	ELY	COL
	BC2-NONEN	CRP	COL
	HC2-CON_COMB	COL	OUT
	HC2-CON_LOSS	COL	OUT
	HC2-IN_BO	TRN, OME, OMN, FPR, LUM, CNS, TWL, OMF, AGR	COL
	HC2-IN_OCTOT	I_S, CRP, NFM,	COL

		NMM, PPP	
	HC2-DOM	PRI	COL
	HC2-PP_EX_WB	ELY	COL
	HC2-PP_EX_OTH	ELY	COL
	HC2-PP_NEW	ELY	COL
	BC2-PP_NEW	ELY	COL
	HC3-PP_EX_OTH	ELY	COL
	HC3-PP_NEW	ELY	COL
	OS2-DOM	PRI	ELY
	HC1-PP_NEW	ELY	COL
	OS1-CON_COMB	ELY	OUT
	OS2-CON_COMB	ELY	OUT
	DC-PP_NEW	ELY	COL
	ETH-TRA_RD	T_T	GAS
	MTH-TRA_RD	T_T	GAS
	MTH-TRA_OT	T_T	GAS
	H2-TRA_RD	T_T	ELY
	H2-TRA_OT	T_T	ELY
	H2-CON_LOSS	ELY	OUT
	HC2-NONEN	CRP	OUT

OUT = Domestic Output
CAP = Capital Demand
ELY = Intermediate or Final demand of Electricity services
GAS = Intermediate or Final demand of Gas services
COL = Intermediate or Final demand of Coal services
OIL = Intermediate or Final demand of Oil services

7.2 New Technologies in RAINS

In the RAINS energy sector, the power and district heat plants [PP] are divided into existing [PP_EX] and new [PP_NEW] power plants. The introduction level of new technologies in 2000 varies between countries. In the conversion between GRACE and RAINS, this is accounted for by allowing for introduction of [PP_NEW] in the same rate as is used in the CP_CLE scenario developed within the CAFE programme. The parameters that ensure introduction of new technologies are:

Koeff2020: Index value 2020 for the RAINS sector, given by the corresponding GRACE sector as indicated in the table above
Sum2000: Sum of the activities for all the RAINS Energy and mobile sectors linked to one GRACE sector in 2000, values according to CP_CLE
ProcBase: = Base2020 / SumBase
Base2020: Activity data for the regarded RAINS sector according to CP_CLE baseline in 2020
SumBase: Sum of the activities for all the RAINS Energy and mobile sectors linked to one GRACE sector in 2020, values according to CP_CLE

For any given RAINS sector within the Energy and Mobile sector, in this conversion from GRACE to RAINS, the activity data (A) in 2020 is given by the product of the GRACE growth index, the total activity level of the RAINS sectors related to this GRACE sector and the relative share of each sector to total activity levels in 2020 according to CP_CLE:

$$\mathrm{A}_{i,\, s,\, f,\, 2020} = \mathrm{Koeff2020}_{j,\, s',\, f'} * \mathrm{Sum2000}_{i,\, j,\, s,\, s'\, f,\, f'} * \mathrm{Procbase}_{i,\, j,\, s,\, s',\, f,\, f'}$$

Where:

i, s, f = Country, RAINS sector, RAINS fuel
j, s', f' = GRACE region, GRACE sector, GRACE fuel

It is the parameter Procbase that ensures the introduction of new technologies into the conversion process from GRACE to RAINS. Procbase varies between regions according to the level of new technologies installed.
For the Energy and Mobile sub-sectors in RAINS, the activity data for the years 2005, 2010 and 2015 are given by linear extrapolation between the given value for 2000 and the calculated value for 2020.

Annex 2. Tables of emission data

7.3 CO_2 emissions (Gtonnes C)

Norway*, Sweden, Denmark and Finland

	2000	2005	2010	2015	2020
S1	0.066	0.071	0.076	0.082	0.088
S2	0.066	0.071	0.066	0.070	0.069
S4	0.066	0.071	0.066	0.072	0.073
S5	0.066	0.071	0.066	0.070	0.068
S6	0.066	0.071	0.066	0.070	0.070
S7	0.066	0.071	0.066	0.071	0.070
S8NoT	0.066	0.071	0.066	0.063	0.059
S8T	0.066	0.071	0.066	0.072	0.074

Other EU

	2000	2005	2010	2015	2020
S1	1.058	1.134	1.216	1.304	1.398
S2	1.058	1.134	1.066	1.084	1.056
S4	1.058	1.134	1.066	1.112	1.122
S5	1.058	1.134	1.066	1.079	1.044
S6	1.058	1.134	1.066	1.083	1.056
S7	1.058	1.134	1.066	1.081	1.054
S8NoT	1.058	1.134	1.066	0.968	0.921
S8T	1.058	1.134	1.066	1.116	1.130

Rest Europe

	2000	2005	2010	2015	2020
S1	0.457	0.514	0.573	0.633	0.695
S2	0.457	0.514	0.575	0.447	0.411
S4	0.457	0.514	0.575	0.472	0.461
S5	0.457	0.514	0.574	0.452	0.424
S6	0.457	0.514	0.575	0.447	0.410
S7	0.457	0.514	0.575	0.450	0.413
S8NoT	0.457	0.514	0.575	0.644	0.715
S8T	0.457	0.514	0.575	0.476	0.471

* Including Iceland and Lichtenstein

7.4 SO_2 emissions (ktonnes SO_2)

Norway*, Sweden, Denmark and Finland

	2000	2005	2010	2015	2020
S1	197	198	205	215	229
S2	197	198	184	195	198
S4	197	198	184	197	203
S5	197	198	185	195	197
S6	197	198	184	195	197
S7	197	198	183	195	198
S8NoT	197	198	184	181	174
S8T	197	198	184	197	203

EU-15 (except Sweden, Denmark and Finland)

	2000	2005	2010	2015	2020
S1	6260	5404	4051	4104	3806
S2	6260	5409	3284	3331	2947
S4	6260	5409	3284	3433	3131
S5	6260	5409	3259	3283	2862
S6	6260	5409	3284	3344	2971
S7	6260	5409	3280	3372	3005
S8NoT	6260	5409	3284	2802	2133
S8T	6260	5409	3284	3448	3158

EU-10

	2000	2005	2010	2015	2020
S1	2775	2401	2147	1965	1802
S2	2775	2416	2099	1272	1040
S4	2775	2416	2100	1350	1158
S5	2775	2416	2101	1273	1051
S6	2775	2416	2099	1287	1055
S7	2775	2416	2099	1283	1046
S8NoT	2775	2416	2100	1143	1026
S8T	2775	2416	2099	1359	1172

Rest of Europe

	2000	2005	2010	2015	2020
S1	9823	9735	9945	10122	10334
S2	9823	9735	10013	7218	6150
S4	9823	9730	10009	7582	6898
S5	9823	9735	10004	7159	6083
S6	9823	9735	10013	7282	6240
S7	9823	9735	10013	7315	6323
S8NoT	9823	9735	10013	10402	10973
S8T	9823	9735	10013	7624	6993

* Including Iceland and Lichtenstein

7.5 NO_x emissions (ktonnes NO_x)

Norway*, Sweden, Denmark and Finland

	2000	2005	2010	2015	2020
S1	886	814	751	693	660
S2	886	814	714	652	610
S4	886	814	714	658	622
S5	886	814	715	652	608
S6	886	814	714	653	611
S7	886	814	714	653	611
S8NoT	886	814	714	623	568
S8T	886	814	714	659	623

EU-15 (except Sweden, Denmark and Finland)

	2000	2005	2010	2015	2020
S1	9355	8323	7497	6767	6217
S2	9355	8323	6797	6045	5304
S4	9355	8323	6797	6152	5527
S5	9355	8323	6817	6048	5293
S6	9355	8323	6797	6047	5309
S7	9355	8323	6799	6041	5307
S8NoT	9355	8323	6797	5509	4532
S8T	9355	8323	6797	6166	5557

EU-10

	2000	2005	2010	2015	2020
S1	1694	1532	1303	1169	991
S2	1694	1532	1239	873	672
S4	1694	1532	1239	907	732
S5	1694	1532	1240	869	677
S6	1694	1532	1239	879	679
S7	1694	1532	1239	878	678
S8NoT	1694	1532	1239	756	599
S8T	1694	1532	1239	911	739

Rest of Europe

	2000	2005	2010	2015	2020
S1	5996	6384	6497	6769	7204
S2	5996	6384	6512	6247	6434
S4	5996	6384	6512	6331	6639
S5	5996	6384	6510	6341	6601
S6	5996	6384	6512	6264	6463
S7	5996	6384	6511	6113	6204
S8NoT	5996	6384	6512	6838	7397
S8T	5996	6384	6512	6340	6659

* Including Iceland and Lichtenstein

7.6 PM emissions (ktonnes PM)

Norway*, Sweden, Denmark and Finland

	2000	2005	2010	2015	2020
S1	154	145	129	123	119
S2	154	145	124	117	109
S4	154	145	124	118	113
S5	154	145	123	116	107
S6	154	145	124	117	110
S7	154	145	124	117	110
S8NoT	154	145	124	108	91
S8T	154	145	124	118	113

EU-15 (except Sweden, Denmark and Finland)

	2000	2005	2010	2015	2020
S1	1201	1046	902	824	793
S2	1201	1046	852	787	732
S4	1201	1046	852	794	752
S5	1201	1046	849	783	721
S6	1201	1046	852	788	735
S7	1201	1046	853	789	738
S8NoT	1201	1046	852	738	630
S8T	1201	1046	852	795	754

EU-10

	2000	2005	2010	2015	2020
S1	427	367	328	307	222
S2	427	367	321	261	179
S4	427	367	321	267	188
S5	427	367	321	258	175
S6	427	367	321	262	179
S7	427	367	321	255	181
S8NoT	427	367	321	200	180
S8T	427	367	321	268	189

Rest of Europe

	2000	2005	2010	2015	2020
S1	1712	1935	1961	2250	2524
S2	1712	1935	1973	1837	1893
S4	1712	1935	1973	1902	2049
S5	1712	1935	1974	1813	1841
S6	1712	1935	1973	1846	1908
S7	1712	1935	1973	1801	1859
S8NoT	1712	1935	1973	2238	2170
S8T	1712	1935	1973	1912	2081

* Including Iceland and Lichtenstein

7.7 Sectoral PM$_{2.5}$ emissions in Finland in 2020 (ktonnes PM) based on the FRES model

	2000	2020							
		S1	S2	S4	S5	S6	S7	S8NoT	S8t
Power plants & industrial comb.	6.1	6.5	6.7	7.0	6.5	6.8	6.8	7.0	7.0
Industrial processes	3.1	3.4	2.8	3.2	2.7	2.9	3.0	3.2	3.2
Domestic combustion	14.1	13.7	12.2	12.9	11.7	12.3	12.8	12.8	12.8
Traffic	7.9	2.3	2.3	2.3	2.2	2.3	2.2	2.3	2.3
Other sources	5.0	6.7	6.5	6.6	6.3	6.5	6.5	6.5	6.5
Total	**36.3**	**32.6**	**30.4**	**31.9**	**29.5**	**30.7**	**31.3**	**31.7**	**31.7**

*The RAINS model for Finland was under thorough revision at the moment of this study. Therefore RAINS emissions were not directly used. Instead, the emissions of the FRES model were used as baseline (S2) scenario emissions. For the other scenarios, the relative sectoral changes in PM emissions of the RAINS model runs of this study were converted to FRES. The emissions of the FRES model correspond approximately to the emissions that will appear in RAINS after the revision of autumn 2006.

Annex 3. Effects

Acididity Unprotected ecosystems 2020	S1 (1000 ha)	S2 (1000 ha)	S4 (1000 ha)	S5 (1000 ha)	S6 (1000 ha)	S7 (1000 ha)	S8T (1000 ha)	S8NoT (1000 ha)
Nordic	6298	4161	4682	4194	4249	4273	4724	5188
EU-15	3342	2317	2471	2300	2347	2359	2500	1817
EU-10	835	337	403	347	355	357	418	334
Other Europe	11422	1391	3969	1491	1791	1946	4715	11229

Nutrient N Unprotected ecosystems 2020	S1 (1000 ha)	S2 (1000 ha)	S4 (1000 ha)	S5 (1000 ha)	S6 (1000 ha)	S7 (1000 ha)	S8T (1000 ha)	S8NoT (1000 ha)
Nordic	4994	4061	4284	4099	4064	4001	4334	3817
EU-15	45766	42949	43641	43136	43161	43156	43846	41202
EU-10	22243	20915	21125	21123	21120	21124	21375	20781
Other Europe	43089	37630	39084	37944	37206	36433	40175	42650

Ozone AOT mean 2020 (1000 km^2 excess ppm.h, cumulative)	S2	S4	S5	S6	S7	S8NoT
Nordic	38	41	38	38	38	32
EU-15	6087	6241	6125	6151	6152	5574
EU-10	1192	1269	1197	1198	1202	1131
Other Europe	2877	3069	2883	2826	2803	3365