

The comments of both referees are on black font below, and the authors' response in on blue.

Referee # 1 (anonymous)

Referee's comment

The paper aims at estimating monetized health impacts caused by emissions of 1 t of PM_{2.5} or 1 t of PM_{2.5} precursors. The monetized health impacts are given distinguishing between emissions of main source categories and emissions in urban vs. non-urban areas. The calculation is made according to the state of science; the science used is sound, the methodology is well described, calculations have been thoroughly made.

Authors' response

Thank you for these positive comments.

Author's changes in manuscript

No changes made.

Referee's comment

However, progress beyond the current state is not made, new developments are not addressed.

Authors' response

The manuscript includes also progress beyond the current state-of-the-art. However, we have not highlighted these sufficiently well in the original manuscript.

First, the emission and partly also dispersion modelling has been performed using a very fine spatial resolution, up to 250 x 250 m²; these have not previously been used for such a geographically extensive area. In comparison, e.g., Heo et al. (2016) used as the basic material the predicted concentrations on a spatial resolution of 36 x 36 km², i.e., two orders of magnitude coarser than in the present study. This resolution scale is characteristic of all the previous studies on public health costs.

We have previously shown (Karvosenoja et al., 2010, Korhonen et al., 2019) that the exposure values evaluated using integrated assessment models can be very sensitive to the methodology. In particular, exposure values can substantially increase with an increasing spatial resolution. Karvosenoja et (2010) showed that using a finer spatial resolution, from 10 km to 1 km, resulted in an increase of the population weighed concentration caused by traffic emissions by an order of magnitude. It is therefore essential to use a sufficiently fine model resolution in view of the health impacts. This is especially important for primary particles from emission sources at fairly low emission heights.

Second, we have also considered the health costs related to the PM_{2.5} precursor emissions on a much finer spatial resolution (5 x 5 km²) than any previous corresponding study. A couple of previous studies have considered precursors (Muller and Mendehlson, 2009, Heo et al. 2016). However, both of the above mentioned studies addressed the U.S. as their modelling domain, Heo et al. (2016) on a resolution of tens of km. The resolution used in the study of Muller and

Mendehilson (2009) was not reported, but considering their results suggests a resolution of tens of km. Air chemistry and the formation of particulate matter is strongly dependent on the chemical composition of the emitted pollutants and climatic factors; the above mentioned American studies can therefore not per se be generalized for European conditions. In addition, we have also allowed for the organic PM in our computations; this was not taken into account by Muller and Mendehilson (2009) or Heo et al. (2016).

Third, we have also programmed an internet-based computation tool, which is publicly available. We expect that this concept and the methods included within this easy-to-use tool would be useful also internationally.

Fourth, the manuscript includes a thorough, up-to-date literature review in this field (in the introductory section). Such a detailed review has not previously been presented in the literature. We have also reviewed in detail the current methods for evaluating the health impacts (in section 2.3) and economic impacts (section 2.4).

Although several public health cost studies with similar aims have been conducted in the U.S., reviewed European articles on health costs are much more scarce. Such studies will need to be done and published for several European regions, for various pollutants, and using different methodologies.

This is needed, as the relevant environmental conditions, such as air chemistry, population densities, the structure of emission source categories, the economic costs of life years, and many other relevant factors, are substantially different in various parts of Europe. The range of uncertainty in such estimates is also large, as shown also in the present study. For consolidating such estimates for various regions, pollutants, methods, etc., therefore requires that such evaluations will be presented for several European regions.

Author's changes in manuscript

We have restructured and revised the conclusions section; the revised conclusions contains a more explicit and clear description on what new developments were introduced in this study, in the context of previous literature.

Referee's comment

An example for currently analysed improvements of the methodology is accounting for NO₂ impacts, which the WHO now considers as likely, though less certain than PM_{2.5} impacts.

Authors' response

This is indeed a relevant and timely comment. Especially older diesel cars emit significant amounts of oxides of nitrogen. As diesel cars have become more common, there has been an intense debate about the need to curb NO₂ emissions in Europe. Long-term exposure to NO₂ has been associated with increased mortality in many epidemiological studies.

However, separation of the effects of NO₂ from the effects of particulate matter is challenging, due to their high correlation. Because of major uncertainties concerning concentration response functions, we did not include NO₂ in this study. WHO has also acknowledged that the effects of NO₂ are partly overlapping with PM_{2.5} effects in epidemiological studies (WHO, 2013).

Author's changes in manuscript

We have added a clarification on why the direct health impacts of NO₂ were not addressed in this study, to the second last paragraph of the introductory section.

Referee's comment

Another issue is using exposure (i.e. concentration where people are) instead of concentration in the background, which would involve analysing also indoor sources (smoking, frying, wood heating).

Authors' response

We totally agree that this is an important new research direction. Some of the present authors have studied this matter by detailed modelling for Helsinki (e.g., Kousa et al., 2002, Soares et al., 2014, Kukkonen et al., 2016) and for London (Smith et al., 2016, Vikas et al, 2019). These studies have allowed also for the movements of the population in various micro-environments, and the infiltration of pollution to indoor air. However, performing such modelling for an entire country would require a substantial amount of work. In our view, this could be a topic of another separate study.

Author's changes in manuscript

We have added a paragraph on dynamic exposure modelling to the conclusions section (next to the last paragraph).

Referee's comment

Another field is source apportionment to improve the large uncertainty of atmospheric modelling. In the text, a small chapter should at least mention current work on improving the methodology. A new part is the calculation of health impacts for emissions of different source groups like transport, residential a.s.o. Up to now, monetized health impacts have been estimated differentiated according to height of release and urban/nonurban area (see e.g. <http://ecoweb.ier.uni-stuttgart.de/EcoSenseLE/current/index.php>). Some important (now older, but still valid) guidelines for the methodology could be cited, e.g. the Externe Externalities of Energy Methodology 2005 Update; downloadable at http://www.externe.info/externe_d7/?q=node/30 or the IEHIAS Integrated Environmental Health Impact Assessment System (2011); web based guidance system; accessible under www.integrated-assessment.eu .

Authors' response

Emission and atmospheric modelling in this study has been substantially improved, compared with previous studies, especially concerning the national very fine resolution emission inventory and numerous recent refinements of the SILAM model. Some recent references have been added regarding the SILAM, FRES and UDM-FMI models, which illustrate the most recent advancements of these models.

We agree with the reviewer that a discussion and references on the EcoSenseLE and ExterneE need to be added to the literature review and to the relevant sections in the text (e.g., Bickel and Friedrich, 2005). Clearly, these are very important research methods and activities in this area, and certainly need to be discussed and referenced.

Author's changes in manuscript

We have added discussion on the methodology of Bickel and Friedrich (2005), and the EcoSenseLE tool to the introduction (4th paragraph).

We have updated the references to the FRES model to include two latest published articles (section 2.1, first paragraph). The references regarding the SILAM model and its applications have been updated in section 2.2., first paragraph and section 2.2.1, first paragraph. One recent reference has been added on the evaluation of the UDM-FMI model (section 2.2.2).

We have also added to the conclusions section a discussion on model improvements in the present study, as per reviewer request, especially regarding the spatial resolutions and organic particulate matter. We have mentioned that one important chemical constituent of the PM_{2.5} that has been neglected, according to our knowledge, by all of the previous published health cost studies has been here taken into account, viz. the organic particulate matter. We could take this fraction realistically into account, due to recent developments of the SILAM model. However, we felt that a more deep and thorough discussion on the improvement of chemical transport and other dispersion models would be outside the scope of this study.

Referee's comment

The result is indeed useful for consultants or decision makers in Finland, that want to identify the most efficient measures for reducing health effects from fine particles. They may use the given unit cost figures for estimating the health benefit caused by reduced emissions, and could also use the tool provided. The editors should decide, whether the publication fits into the scope of their journal or whether a journal more oriented towards environmental policy application might be a better choice

Authors' response

In the authors' view, the paper would fit best to the scope of ACP.

Author's changes in manuscript

No changes made.

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Referee # 2 (Ståle Navrud)

Referee's comment

Interactive comment on “Modelling of the public health costs of fine particulate matter and results for Finland in 2015” by Jaakko Kukkonen et al.

Ståle Navrud (Referee) stale.navrud@nmbu.no Received and published: 12 May 2020

This paper is an excellent and state-of-the-art application of the impact pathway approach (also termed the damage cost approach by economists) to assess public health costs of fine particulate matter (PM_{2.5}) in ambient air from domestic primary and precursor emissions of PM_{2.5} in Finland in 2015. The paper provides a very transparent overview of the assumptions and calculations in all steps of the impact pathway model they develop; from emissions from different sources through dispersion and exposure to concentration-response functions and the economic valuation of the selected health endpoints.

Authors' response

Thank you for these positive comments.

Author's changes in manuscript

No changes made.

In the economic valuation of premature death due to PM2.5 the authors argue for using the number of lost life years and the Value of a Life Year (VOLY) rather than valuing all people at the Value of Statistical Life (VSL). This implies assigning a lower value to the elderly, that make up the majority of people dying prematurely due to PM2.5. The authors state in line 402-407: “The monetized estimates in the computations of the economic impacts in this study are based on the average value of a life year (VOLY), instead of the value of statistical life (VSL). The VOLY-based approach has been commonly used as a measure to assess a decrease in mortality risk (Im et al., 2018), whereas the VSL-based approach, despite its disadvantage, is in line with EPA’s standard procedure and recommendations (Wolfe et al., 2019)”. The “despite disadvantages” phrase should be deleted. They should instead say choosing between the VSL and VOLY approaches is also an ethical question in terms of whether one should assign the same economic value to all adults, independent of age; and that a constant VOLY assumes that people value a life year the same independent of age.

Authors' response

There was an unfortunate error in our text in the manuscript. In the method section 2.4. (lines 402-407 in the original manuscript), we should write that both VOLY and VSL -based methods were used. This is how we actually used the methods in the ‘results’ section, and how we described the conclusions.

We also agree that ‘despite disadvantages’ should be removed, and that selection between these two measures is partly an ethical question.

Author's changes in manuscript

We have corrected the error mentioned above (the revised manuscript version reads that we use both VOLY and VSL).

We have deleted the phrase “despite disadvantages“, in relation to VSL. We have also somewhat restructured the 2nd and 3rd paragraphs of the section 2.4 to be more logical.

Also the authors further down in the paper (line 669-672) say that they have performed calculations using both VOLY and VSL (see also table 4), in order to show the difference in calculated economic benefits from emission reductions; which is of course very good that they do. However, in line 402 (see citation above) they state that they only used VOLY. This has to be corrected to made consistent with the calculations/sensitivity analyses they actually performed.

Authors' response

We thank the reviewer for finding this mistake in the original manuscript.

Author's changes in manuscript

We have corrected the mistake.

In line 399 after the sentence “This also facilitates numerical comparisons with those studies” they should add that: “Ideally a country-specific VSL (and a derived VOLY from this VSL) for Finland should be applied in this analysis, which could be based on value transfer (Navrud and Ready 2008) from the most recent global meta analysis of stated preference studies of VSL (Lindhjem et al 2011). However, this would preclude the direct comparison of results with similar impact pathway models e.g. Holland et al (2005).

Authors’ response

We agree with the reviewer on this comment and thank him for providing this text.

Author's changes in manuscript

We have added this comment to the manuscript (2nd paragraph of section 2.4).

In the appendix the authors use VOLY as the abbreviation for Value of a Life Year , whereas in the text also VLY is used (e.g. in the paragraphs including lines 670, 685 and 705). This should be consistent, and I suggest using VOLY all the way through the paper.

Authors’ response

We agree.

Author's changes in manuscript

All such acronyms have been corrected to read ‘VOLY’.

They find that the economic benefits om emission reductions are clearly largest for the emission reductions for the source categories that have low emission heights, and are located in more densely populated regions (i.e. vehicular traffic, non-road and machinery and residential wood combustion urban versus rural areas). In the Abstract they say “It was found that economically the most effective measures would be the reduction of the emissions in urban areas of (i) road transport, (ii) non-road vehicles and machinery, and (iii) residential wood combustion”. However, in economics cost-effectiveness, that this can statement can interpreted as, is a measure of e.g. reduced number of kg of PM 2.5 emissions per euro of abatement costs. Thus, the authors should rather say that “ the economic benefits in terms of avoided public health costs is largest for measures that will reduce of (i) road transport, (ii) non-road vehicles and machinery, and (iii) residential wood combustion”. Whether these measures have the largest net benefits (Economic health benefits minus the abatement costs) depends of course on the costs of reducing emissions from theses sources.

Authors’ response

We totally agree with the reviewer, this is an important point.

Author's changes in manuscript

We have corrected this mistake in the abstract.

This also has to be corrected when using the word “effective” both in the abstract and in line 399-805.

Authors' response

We have checked the whole manuscript for the correct usage of terminology in this respect.

Author's changes in manuscript

We have revised the text at several instances, to be in accordance with the correct terminology, as per reviewer request.

There could also be other economic benefits than to public health from reducing the PM2.5 emissions, such as reduced soiling and corrosion of residential and commercial buildings, historic monuments and cultural heritage buildings as well as reduced environmental damages. The authors very briefly mentions this at the end of the paper, but they could also mention that there are ways to value these economic benefits and refer to e.g. Navrud and Ready (2002, 2007) and Watt et al (2009).

Authors' response

We agree on this comment.

Author's changes in manuscript

The first paragraph in the introduction has been extended to include these comments and references.

References:

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Author's changes in manuscript

The above mentioned references were added to the reference list.

Other minor revisions**Author's changes in manuscript**

In the affiliations on the first page, we have added the acronym 'SYKE', as this institutes prefers to write its name in this manner. The name of the third institute has also been updated. A second affiliation has been added to Prof. Lanki.

Modelling of the public health costs of fine particulate matter and results for Finland in 2015

5 Kukkonen, Jaakko¹, Mikko Savolahti², Yuliia Palamarchuk¹, Timo Lanki^{3,4}, Väinö Nurmi¹, Ville-Veikko Paunu², Leena Kangas¹, Mikhail Sofiev¹, Ari Karppinen¹, Androniki Maragkidou¹, Pekka Tiittanen³, Niko Karvosenoja²

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15 **Abstract.** We have developed an integrated tool of assessment that can be used for evaluating the public health costs caused by the concentrations of fine particulate matter (PM_{2.5}) in ambient air. The model can be used in assessing the impacts of various alternative air quality abatement measures, policies and strategies. The model has been applied for the evaluation of the costs of the domestic emissions that influence the concentrations of PM_{2.5} in Finland in 2015. The model includes the
20 impacts on human health; however, it does not address the impacts on climate change or the state of the environment. First, the national Finnish emissions were evaluated using the Finnish Regional Emission Scenarios model (FRES) on a resolution of 250 x 250 m² for the whole of Finland. Second, the atmospheric dispersion was analyzed by using the chemical transport model SILAM and the source-receptor matrices contained in the FRES model. Third, the health impacts were assessed by combining
25 the spatially resolved concentration and population datasets, and by analyzing the impacts for various health outcomes. Fourth, the economic impacts for the health outcomes were evaluated. The model can be used to evaluate the costs of the health damages for various emission source categories, for a unit of emissions of PM_{2.5}. It was found that the economic benefits in terms of avoided public health costs were largest for measures that will reduce the emissions of (i) road transport, (ii) non-road vehicles and machinery, and (iii) residential wood combustion. The reduction of the precursor emissions of PM_{2.5}
30 resulted in clearly lower benefits, compared with reducing directly the emissions of PM_{2.5}. We have also designed a user-friendly web-based tool of assessment that is available open access.

35 1. Introduction

Air pollution related to particulate matter (PM) can result in a wide variety of impacts. Prominent
40 examples of these include enhancement or mitigation of climate change, adverse impacts on the health of the populations, and various consequences on the environment (e.g., influence on biodiversity, acidification and eutrophication). Air pollution may also cause corrosion of materials and degradation of buildings and cultural heritage (e.g., Al-Thani et al., 2018). Methods to analyze and value such economic benefits have been presented, e.g., by Navrud and Ready (2002, 2007) and Watt et al (2009). This study focuses on the impacts of air pollution on public health. The projected economic growth, urbanization and the increased fraction of senior population will increase the effects on public health in
45 some regions in the future (e.g., OECD, 2016).

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55 Emission standards and other control policies in many cases address only the amounts of emissions. Such policies will not be optimal for the mitigation of the impacts of poor air quality, as the same amount of emissions from different sources may have totally different damage costs (e.g., Muller and Mendehlson, 2009; Carson and LaRiviere, 2018). Economists have therefore suggested market-based approaches, such as emission taxes (e.g., Baumol and Oates, 1998) or tradable permits. As the marginal damages (defined as the additional damage caused by an additional unit of emission) and the properties of the emission sources, such as emission heights, differ across regions (Nahlik et al., 2016), environmental policies should reflect these differences. It is therefore worthwhile to evaluate the relative costs for potential emission reductions from different emission source categories located in different regions.

60 There is a fairly extensive amount of scientific literature regarding the cost evaluations of air pollution on public health, including especially the effects of the PM_{2.5} concentrations. Muller and Mendehlson (2009), Holland et al. (2015) and Heo et al. (2016) have evaluated the unit costs for the emissions at various stack heights on a fairly fine spatial resolution in the United States at a county level. Buconore et al. (2014), Levy et al. (2009) and Fann et al. (2009) have conducted similar studies on a coarser resolution in the United States. Moreover, Nahlik et al. (2016) estimated the county-specific unit damage costs for PM (especially PM_{2.5}), in addition to SO_x, NO_x and VOCs at major airports in the United States. Trejo-González et al. (2019) analyzed economic costs associated with exposure to PM_{2.5} in 2013 and 2015 in Mexican cities assuming two mitigation scenarios.

75 In Europe, Bickel and Friedrich (2005) have developed a thorough methodology for the impact pathway approach, called the ExternE methodology. The ExternE methodology provides a framework for presenting numerous various impacts as monetary values. In particular, Bickel and Friedrich (2005) have evaluated monetized health impacts, differentiated according to height of release and urban versus non-urban area. They also developed an assessment tool called EcoSenseLE (Light Edition) to easily provide for estimations of impacts on human health and of environmental damages caused by air pollution in Europe (<http://ecoweb.ier.uni-stuttgart.de/EcoSenseLE/current/index.php>). More recently, Holland et al. (2014) and Brandt et al. (2010) have evaluated unit costs at country level. Defra (2015) and Walton et al. (2015) have conducted similar studies regionally in Europe.

80 In Asia, and more specifically in China, Qi et al. (2018) investigated the losses as well as the consequences caused in the economy by ambient PM_{2.5}. The study by OECD (2016a) pointed out that impacts due to PM_{2.5} concentrations commonly contribute to more than 90 % of the total health costs of air pollution. Clearly, the exact proportion of these effects substantially depends on the domain and the year of evaluation. Emissions of the most important PM_{2.5} precursors, such as NO_x, SO₂ and NH₃, have also been included in some studies (e.g., Walton et al., 2015). The direct health costs of NO₂ and O₃ may also be substantial in some cases.

90 With respect to unit cost modelling, most studies have used the so-called impact pathway approach. This approach combines air quality modelling with population data, epidemiological evidence and economic modelling (Im et al., 2018). It is a sequential approach, in which one assumes a change in emissions, models the corresponding changes in air quality, uses epidemiological evidence to calculate the health response, and finally applies economic evidence. For instance, Trejo-González et al. (2019) concluded in their study that a reduction of the annual PM_{2.5} average to less than 10 µg/m³ in 2015

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would have decreased mortality by 14,666 (avoidable deaths) with estimated costs of 64,164 million dollars in Mexican cities.

105 Some previous studies have used chemical transport models on regional or continental scales (e.g.,
Fann et al., 2009; Buonore et al., 2014; Brandt et al., 2010; Im et al., 2018). Another approach is to use
simplified decision-support modelling systems that use pre-computed atmospheric dispersion statistics
or source - dispersion matrices (e.g., Muller and Mendehlson, 2009, Holland et al., 2014, 2015, Bickel
110 et al., 2003). One example of such approaches was presented by Heo et al. (2016); they attempted to
generalize the results of chemical transport models using statistical methods. As this approach
substantially reduces the computational effort, one can evaluate a much larger number of various
emission reduction scenarios. Heo et al. (2016) computed the resulting changes in air quality for a one
ton reduction in emissions for 11 different emission sources in United States.

115 In the next stage of the evaluation, one will evaluate the health impacts caused by the changes in the
concentrations. Some of the studies have included only the increased risk of early mortality. (e.g. Heo
et al. 2016; Buonocore et al. 2014; Levy et al. 2009), due to the fact that mortality costs commonly
dominate the total unit costs. In these studies, PM_{2.5} induced mortality has been modelled with a linear
response-function model, in which an increase in the concentration levels is linearly translated into
120 either to loss of human lives or years of life lost (YOLL) years. For example, 144,289 and 150,771
potential YOLLs due to exposure to PM_{2.5} were estimated for 2013 and 2015, respectively, in Mexican
cities (Trejo-González et al. (2019)

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The response functions have been estimated in epidemiological studies, such as Pope et al. (2002) or
125 based on a combination of other studies related to long-term exposure to PM_{2.5} and PM₁₀, such as
Trejo-González et al. (2019). However, most studies have also included other end-points; commonly at
least morbidity costs (Muller and Menhdelson, 2009; Holland et al. 2016; Fann et al. 2009; Walton et
al. 2015; Defra, 2015; EEA, 2014). Some studies (Muller and Mendehlson, 2009; Walton et al. 2015)
130 have also included the loss of agricultural yields; however, resulting on minor effect on the unit costs. In
a more recent study conducted by Trejo-González et al. (2019) the lost productivity was also calculated
for 2013 and 2015 in Mexican cities for different age groups (15 and more, 30 and more, and 25 to 74
years). In China, Qi et al. (2018) estimated that the total national loss due to exposure to PM_{2.5} was
79.2 billion RMB ¥.

135 As the increased risk of early mortality commonly dominate the unit cost estimates, the assumptions
behind its computation explain a large fraction of the variation in various damage cost estimates. The
health response-functions contain a risk ratio or relative risk (RR) for an increase in concentration of 10
µg/m³ that describes the change in the relative risk level. Relative risk (RR) is generally defined as the
ratio of the probability of an outcome in an exposed group to the probability of an outcome in an
140 unexposed group. Moreover, RR is different from one region to another depending on ambient PM_{2.5}
composition and the variation in people's sensitivity (Qi et., 2018) A low value was applied by Bicket
et al. (2003), RR = 1.024, whereas Pope et al. (2002) estimated a much higher value, RR = 1.077. The
latter estimate has been widely used in unit cost studies (Muller and Mendehlson, 2009; Holland et al.
2016; EEA, 2014). Qi et al. (2018) also applied a low RR for lung cancer related to PM_{2.5} in China and
145 it was equal to 1.03. The same value was used by Cao et al. (2011) and Loomis, Huang, and Che
(2014). American Cancer Society published an estimate of 1.075 that was used in Heo et al. (2016). A
more conservative estimate of 1.06 has been reported in some studies such as Defra et al. (2015 and
Raza et al. (2018), apart from Woodcock et al. (2009; 2013;2014) and Dhondt et al. (2013). The

150 Harvard Six Cities -study (Laden et al., 2006) resulted in an even more substantial mortality, i.e., RR = 1.12. This value has also been used widely (Fann et al. 2009; Levy et al. 2009). Raza et al. (2018) presented an even higher RR for PM_{2.5} (RR=1.17) in their paper which was originally reported in another study regarding air pollution and mortality in Los Angeles (Jerrett et al., 2005)

155 Next step in the analysis chain is to convert the health impacts into monetary values. With respect to mortality, there are two main approaches for the monetary valuation: either (i) counting the expected value of life years lost and multiplying with the value of a life year (VOLY), or (ii) counting the expected value of early mortality and multiplying with the value of life (VSL). However, both the values of VOLY's and those of VSL's, and the final cost results obtained using these two approaches can vary substantially. Regarding the VSL, a fairly low estimated value in Muller and Mendehlson (2009) was two million dollars, with an age-adjusted value of 1.2 million dollars, whereas Heo et al. (2016) evaluated VSL to be 8.6 million dollars. VSL was equal to 1.629 and 1.643 million dollars in 2013 and 2015, respectively, in Mexican cities of the National Urban System (Trejo-González et al. 2019) EU-based studies have commonly indicated a higher public health cost value using the VSL-method, compared with those obtained using VOLY; e.g., the study by EEA (2014) found that the VSL-based values were approximately 2.5 higher than the VOLY-based values.

170 Taking into account the concentrations nowadays and during the past decade, particulate matter can be considered in most locations to be more harmful than gaseous pollutants; e.g., this has been found to be the case for the Nordic countries by Hänninen et al. (2016), Lehtomäki et al. (2018) and Kukkonen et al. (2018). WHO (2013a) has evidenced a strong association between the concentrations of coarse and ultrafine particles and harmful effects. In the present study, we have addressed the health impacts of fine particulate matter, including also its precursor emissions; however, we have selected not to consider the health effects of NO₂ concentrations. WHO has stated that the effects of NO₂ are partly overlapping with those of PM_{2.5} in epidemiological studies (WHO, 2013a,b). The main reason for not addressing NO₂ health impacts in this study were the major uncertainties concerning concentration response functions. A majority of epidemiological studies have focused on PM_{2.5}, or alternatively on PM₁₀, including PM_{2.5} as a sub-fraction, and therefore the most established concentration-response functions have been developed for these size fractions.

180 The overarching aim of this study is to develop an integrated tool of assessment for evaluating the public health costs caused by the ambient air concentrations of fine particulate matter (PM_{2.5}). The objectives of this study were (i) to present an impact pathway model for evaluating the public health costs due to the concentrations of PM_{2.5}, (ii) to present selected example results regarding the various stages of this assessment for domestic pollution sources in Finland in 2015, and (iii) to present both an easy-to-use summary tabulation and a web-based computation system of the public health costs for various emission categories. The final model framework includes emission and dispersion modelling, health impact assessment and economic evaluation. The model and results regarding the costs of the emissions from various source categories can be used to assess the economic public health impacts of national and urban scale air quality strategies and those of various potential emission mitigation measures. The model framework could be also adapted for similar economic cost analyses in other countries or geographical domains in the future.

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195 2 Methods

This study adopts the impact pathway approach, to combine the various modelling stages.

2.1 Inventory of the domestic emissions

The anthropogenic emissions in Finland in 2015 were computed using the Finnish Regional Emission Scenarios model (FRES). For a detailed description of the FRES model, the reader is referred to Karvosenoja (2008), Karvosenoja et al. (2011, 2020) and Savolahti et al. (2016, 2019). The modelling included the anthropogenic emissions of the compounds PM₁₀, PM_{2.5}, PM₁, BC (black carbon), OC (organic carbon), mineral dust, SO₂, NO_x, NH₃, NMVOC and CO. The emissions were computed on a grid of 250 m x 250 m for the whole of Finland, for various area sources. In addition, the modelling included 424 industrial point sources. For the latter, coordinates and stack heights were used that were specific for each installation (Karvosenoja et al., 2011).

The emission scenarios included the most significant pollutants for each source category. These included the primary emissions as follows: PM_{2.5}, NO_x and SO₂ for industrial installations and power plants, PM_{2.5} and NO_x for vehicular traffic and machineries, PM_{2.5} for residential wood combustion, and NH₃ for agriculture. First, we computed a baseline emission scenario for a selected recent year, 2015. Second, the emissions from each of the considered emission sectors and considered pollutants were reduced by a constant moderate percentage, selected to be 10 %, compared with the baseline scenario.

The health damage caused by the population exposure is substantially dependent on the spatial correlation of the distributions of the population and the emission sources (e.g., Soares et al., 2014). Such a correlation can be especially high for vehicular traffic and residential wood combustion. These two emission source categories were therefore separately analyzed for two classes, viz. emissions in urban and non-urban areas. In this study, urban areas were defined according to two criteria: (i) these had to include grid cells (250 m x 250 m) that contained at least 200 residents, and (ii) buildings had not be further from each other than 200 m.

For point sources, we have also treated the PM_{2.5} emissions separately, depending on the location of the facility. This was done, as the population density in the vicinity of various locations varied substantially. We have therefore evaluated separately the unit costs for (i) the Helsinki capital area, (ii) the municipalities of more than 50 000 inhabitants and (iii) the other areas.

2.2 Atmospheric dispersion modelling

We have evaluated the atmospheric dispersion using two models: (i) the chemical transport model SILAM (e.g., Sofiev et al, 2006 and 2015), and (ii) the source receptor matrices contained in the FRES model (Karvosenoja et al., 2011). The SILAM model can be used for regional, continental and global scale evaluations (Sofiev et al, 2018, Lehtomäki et al, 2018, Brasseur et al, 2019), whereas the FRES model is applicable on local and regional scales.

We have used two models, as both their applicability and results are complementary. The model computations using the SILAM model include also the long-range transported contributions from the

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250 rest of Europe, whereas the FRES computations address only the dispersion of the domestic emissions.
Another advantage of the SILAM model computations is that the formation of secondary PM_{2.5} is taken
into account, whereas these are not included in the FRES model computations. On the other hand, the
FRES computations are substantially less resource-consuming, and we therefore could execute the
255 model on a very fine spatial resolution, 250 x 250 m². In this study, we used the SILAM computations
on a resolution of 5 x 5 km² over the Finnish domain.

The impacts of the various domestic emission reduction scenarios were evaluated by numerically
changing the Finnish emissions of a selected source category, whereas the emissions from the other
260 domestic source categories were kept the same. In the SILAM computations, the emissions from the
rest of Europe were also assumed to be the same, for all the emission scenarios. In this way, one can
evaluate the impact of one selected national source category on the concentrations of PM_{2.5}.

First, we computed atmospheric dispersion for the baseline emission scenario in 2015, using actual
meteorological data for that year. Second, the atmospheric dispersion was computed for the reduced
265 emission scenarios described above. Finally, the differences of these two computations were computed,
and the results were converted to correspond to a reduction of a unit mass of emissions.

270 2.2.1 Modelling using the SILAM model on the European and national scales

SILAM is a dispersion model from global to mesoscales that has been developed for evaluating
atmospheric composition (Sofiev et al., 2015). The model is also used for policy guidance in case of
emergencies and for solving inverse dispersion problems. The model includes dispersion and transport
275 treatments using both Eulerian and Lagrangian approaches. The model contains eight chemical and
physical transformation modules, viz. basic acid chemistry and secondary aerosol formation, ozone
formation and transformation in the troposphere and the stratosphere, radioactive decay, aerosol
dynamics and transformation of pollen (Sofiev et al., 2010, Kouznetsov and Sofiev, 2012, Sofiev,
2017). The model components and setup used in the current study have been described and evaluated
by Prank et al. (2016), Kollanus et al. (2016), Petersen et al. (2019) and Karl et al. (2019). The model
280 also includes modules for three- and four-dimensional variational and Ensemble Kalman Filter data
assimilation (Viras and Sofiev, 2012 and 2015, Vira et al., 2017).

The computations using the SILAM model included both global and European scale transport and the
contributions from the domestic (Finnish) emission sources. The modelling for the whole of Finland
285 was carried out on a resolution of five kilometers. A detailed description of these computations has
been previously presented by Lehtomäki et al. (2018).

The SILAM model computations included also the impacts of the chemical and physical
transformations on the formation of secondary PM_{2.5}. These reactions include especially the impacts of
290 the emissions of sulphur, nitrogen and ammonia compounds of both natural and anthropogenic origin
on the concentrations of PM_{2.5}. In the model calculations, the full spectra of emitted compounds were
included, taking separately into account the temporal variations for each individual sector. The
modelling also allowed to treat simultaneously the sectoral specifications of the point and area sources.
This enabled to estimate independently the contributions of the emission reductions on PM_{2.5}
295 concentrations, originated from power plants, industry, traffic and agricultural ammonia.

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2.2.2 Modelling using the FRES model on the national scale

305 The FRES model was applied for the evaluation of the impacts of primary domestic emissions. These computations had a spatial resolution of 250 x 250 m² over the whole of Finland. The source-receptor matrices that were used in this model were based on the computations using the dispersion model UDM-FMI (Urban Dispersion Modelling system by the Finnish Meteorological Institute; e.g., Karppinen et al., 2000a).

310 The UDM-FMI model is based on Gaussian plume equations for multiple sources, including stationary point, area and volume sources. The modelling system including the UDM-FMI model has been previously extensively evaluated versus urban measurement data for gaseous pollutants (e.g., Karppinen et al., 2000b and Kousa et al., 2001) and for PM_{2.5} (e.g., Kauhaniemi et al., 2008, Kukkonen et al., 2018 and 2020).

315 The source receptor matrices were based on separate computations over ten climatic sub-zones in Finland, assuming two different emission heights. Such computations were necessary, as the dispersion processes are strongly dependent on the climatic variation of the relevant meteorological conditions. The computations were performed on an hourly basis for a period of five or six years for each of the ten climatic zones, depending on the availability of the relevant meteorological data. In the final
320 computations using the FRES model, monthly average source-receptor matrices were used.

2.3 Health impact assessment

325 In this assessment, we have not explicitly allowed for the health effects caused by the NO₂ concentrations. One reason for this choice is that in evaluating the health impacts of PM_{2.5}, we have already allowed for the secondary PM_{2.5} concentrations that have resulted from the NO and NO₂ precursor emissions. Including also the health impacts in case of the NO₂ concentrations would therefore result in double counting. Another reason for not explicitly including the health impacts of NO₂ exposure is that the concentration-response function for NO₂ has an effective range for annual average concentrations exceeding 20 ug/m³; the concentrations of NO₂ are commonly lower than this
330 threshold value in the present study.

We have combined the modelled annually averaged concentrations of PM_{2.5} with the population count data provided by Statistics Finland in 2015. These datasets were combined in a 250 x 250 m² grid, for five-yearly age categories. The health effects of PM_{2.5} were assumed to be linear in the concentration
335 range observed in Finland. It was therefore possible to use annual concentration data for the computations of the health impacts regarding both short- and long-term exposures.

We have computed the health impacts for each grid cell (i) within the domain (i.e., the whole of Finland). The exposure of the population to the concentrations of PM_{2.5} in a grid cell is
340

$$PE_i = P_i \times C_i,$$

where P_i and C_i are the population and concentration in the grid cell i, respectively. For each health outcome, the effect of the PM_{2.5} exposure was estimated by calculating the relative excess risk:

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350 $RER = (RR-1) \times 0.1,$

where RR is the risk ratio for PM_{2.5} for the considered health outcome.

365 The computation takes into account that risk ratios for PM_{2.5} are usually presented in terms of a 10 µg/m³ increase in concentration. However, for some health outcomes, reliable risk ratios have only been established for PM₁₀. In such cases, the RER of PM₁₀ multiplied by 1.54 was used, as recommended by WHO (WHO, 2013b). The underlying assumptions in deriving this numerical value were that the PM_{2.5} concentration constitutes 65 % of the PM₁₀ concentration, and the health effects of PM₁₀ can be explained by PM_{2.5}.

360 The number of cases of a considered health outcome in each grid cell was calculated as follows:

$$N_i = PE_i \times RER \times BR ,$$

365 where BR is the background risk of a considered health outcome. The total impact of PM_{2.5} exposure on an outcome was calculated by summing the numbers of cases over all grid cells. We computed the total number of years of life lost due to the PM_{2.5} exposure by (i) multiplying the evaluated deaths with life-expectancy in one-yearly age categories, and (ii) subsequently summing the lost life years over all the age categories.

370 The exposure to fine particulate matter has been reported to be associated with a substantial number of health outcomes in epidemiological studies (Qi et al., 2018; Raza et al., 2018; Im et al., 2018); however, reliable estimates of the concentration-response functions have been derived only for a limited number of outcomes. In this study, the functions recommended within the HRAPIE project were used (WHO, 2013b). These functions have been considered sufficient to enable the quantification
375 of both the effects of the long-term PM_{2.5} exposures on mortality, and the short-term exposures on cardiovascular and respiratory hospital admissions (Im et al., 2018).

380 We did not use any threshold for the PM_{2.5} effects, as even relatively low levels of PM_{2.5} have been associated with health effects (e.g., Halonen et al 2009) and even mortality (WHO, 2013a; Raza et al., 2018). It is also biologically plausible that a threshold for the effects does not exist, due to the nature of the proposed physiological mechanisms of the effects, such as systemic inflammation (e.g., Lanki et al., 2015). However, in some recent global impact assessments, a lower cut-off concentration has been used (Gakidou et al., 2017).

385 We have also made the simplification that the health effects of PM_{2.5} were the same per mass unit for all emission source categories. The chemical composition of PM_{2.5}, and consequently the emission source, has been found to modify the health effects. For example, it has been suggested based on toxicological studies that secondary PM_{2.5} may be less harmful than primary PM_{2.5}. However, the current consensus is that the PM_{2.5} sources cannot be ranked with respect to harmfulness, as the
390 evidence is not sufficient for doing so (WHO 2013a, EPA 2009).

Many of the health effects of PM_{2.5} are lagged in time, whereas in the model all effects are treated as immediate ones. On one hand, the effect of the lag time is irrelevant, if the considered time scale is very long. This is commonly the case for policy measures to curb PM_{2.5} emissions; these are

395 characteristically designed to be long-term solutions. On the other hand, the uncertainty of the cost
estimates will increase over decades, as the population size and location, age structure, background
risks and willingness to pay for better health will inevitably change.

400 The considered health outcomes have been presented in Table 1. These outcomes are mainly long-term
effects. There is sufficient evidence also on the effects of short-term exposures on mortality, but as the
short-term effects can be considered to be included in the estimates of the long-term effects, they were
not explicitly included in the model. Regarding the restricted activity days, we did not include the days
spent in a hospital (based on calculations on hospital admissions) or at home (calculations on lost work
days), to avoid double-counting.

405

410 Table 1. The considered health outcomes, age groups, types of exposure, risk ratios per concentration difference, their confidence intervals and annual background risks.

Outcome	Age group	Exposure	Risk ratio per 10 $\mu\text{g}/\text{m}^3$	Confidence intervals, 95 %	Background risk, yearly
Mortality	> 30 yrs	PM _{2.5} long-term	1.062	1.040-1.083	1345,33 deaths/100,100 (2015)
Cardiovascular hospital admissions	All	PM _{2.5} short-term	1.0091	1.0017-1.0166	26,48/1000 (2014)
Respiratory hospital admissions	All	PM _{2.5} short-term	1.019	0.9982-1.0402	13.91/1000 (2014)
Neonatal infant mortality	1-12 kk	PM ₁₀ long-term	1.04	1.02-1.07	0.77 deaths/1000 live births (2014); 10.12 births/1000 (2015)
Chronic bronchitis, incidence	>18 yrs	PM ₁₀ long-term	1.117	1.040-1.189	3.9 cases/1000
Bronchitis, prevalence	6-12 yrs	PM ₁₀ long-term	1.08	0.98-1.19	186/1000
Work days lost	20-65 yrs, at work	PM _{2.5} 2 week	1.046	1.039-1.053	9.85 days/ person (2008); employment rate 73,2 % (avg. 2011-2015)
Asthma symptoms, incidence	5-19 yrs, asthmatics	PM _{2.5} short-term	1.028	1.006-1.051	35 asthmatics/1000; 17% of days with symptoms
Restricted activity days	\geq 20 yrs	PM _{2.5} 2 week	1.047	1.042-1.053	19 days/ person

415 The evidence for the concentration-response functions is stronger for mortality and hospital admissions, compared with the other health effects listed in Table 1. The concentration-response functions were nevertheless provided also for other health effects in the HRAPIE project. The causal association for these effects can be considered to be probable; however, the magnitude of these effects cannot be precisely determined. We have included such effects in the model to avoid underestimation of the total health impacts. For the mortality, a risk ratio of 1.062 was used, which can be considered to be a state-of-the art value (e.g., Walton et al., 2015).

420

425 Some impacts of PM_{2.5} have not been calculated in the total Finnish population, but in a specific age
group. This selection was caused by the limitations of the epidemiological studies that provided the
concentration-response functions. The HRAPIE project recommends computing the impact of PM_{2.5}
430 exposure on the restrictions of physical functioning without age limitations, although the original
epidemiological study that provided the concentration-response function was conducted in a working-
age population (Ostro 1987). As a compromise, we have computed the impact in both working-age and
elderly populations, but not in children, where the effect was considered to be too uncertain.

435 Concentration-response functions correspond to the relative effects of PM_{2.5}. In addition, information
on the background risk is therefore needed for each outcome, to calculate the actual impact. In this
study, the background risk of mortality was obtained from Statistics Finland, and the information on
hospital admissions from Eurostat. Other estimates of the background risk are based on previous EU-
wide impact assessments (Hurley 2005, Holland 2014).

2.4 Assessment of the economic impacts

440 The economic cost values applied in the computations are presented in Table 2. The costs have been
mainly selected according to the previous EU-wide impact assessments by Hurley et al. (2005) and
Holland (2014). This also facilitates numerical comparisons with those studies. The mortality effects
445 have the largest impact on the total costs; the evaluation of the unit cost for mortality was therefore the
most crucial parameter for the final results.

450 Alternatively, a country-specific VSL (and a derived VOLY from this VSL) for Finland could be
applied in this analysis. Such a value could be based on value transfer (Navrud and Ready, 2008) from
the most recent global meta-analysis of stated preference studies of VSL (Lindhjem et al 2011).
However, this would preclude the direct comparison of results with similar impact pathway models,
such as, e.g., Holland et al (2005).

455 The monetized estimates in the computations of the economic impacts in this study were based both on
the average value of a life year (VOLY) and the value of statistical life (VSL). The selection between
the VOLY and VSL approaches is also an ethical question. In order to obtain more objective results,
less dependent on any ethical evaluations, we selected to use both measures. In the VSL approach, the
increase in relative risk is uniformly applied to all the age groups, whereas in the VOLY approach, the
relative risk is unequally distributed within the various age groups. However, some studies have
adjusted for this factor (e.g., Muller and Mendehlson, 2009). In other words, the selection of VOLY or
460 VSL includes whether one should assign the same economic value to all adults, independent of age.
Assuming a constant VOLY also implies that people value a life year the same way, independently of
their age.

465 The VOLY-based approach has been commonly used as a measure to assess a decrease in mortality
risk (Im et al., 2018), whereas the VSL-based approach is in line with EPA's standard procedure and
recommendations (Wolfe et al., 2019). VSL has been used in many studies in the U.S (i.e. Nahlik et al.,
2016; Trejo-González et al., 2019; Wolfe et al. (2019), while mainly VOLY has been used in the
studies within the EU (Im et al., 2018). The VSL-based approach results in higher economic cost
values (e.g., EEA, 2014).

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490 We have used both average and median values of VOLY in this study. However, the average value may correspond better to the willingness to reduce risks on a population level.

495 Table 2. The unit costs (in euros) of the health outcomes that were included in the model. All values are mainly based on the willingness to pay -approach.

Outcome	Age group	Cost (€)	Additional information
Mortality, value of life	>30 years	2.65 million	Average
Mortality, value of a life year	>30 years	69000 (median) 160000 (average)	Median and average values
Cardiovascular hospital admissions	All	2837	The total sum consists of 628 €, the care costs for three days, 939 €, and the lost work days for five days, 1270 €.
Respiratory hospital admissions	All	2837	The total sum consists of 628 €, the care costs for three days, 939 €, and the lost work days for five days, 1270 €.
Chronic bronchitis, incidence	>18 years	64500	
Bronchitis, prevalence	6-12 years	784	Cough symptom day 56 €, for 14 days
Lost work days	20-65 years at work	254/day	Working time 7.06 hours per day, the cost of each working hour 36 €
Restricted activity days	≥20 years	154/day	Based also on the cost of lost work days

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The unit cost of chronic bronchitis used in this study (200,000 €) was substantially lower than the corresponding value used in the previous EU-wide assessment by Hurley et al. (2005). The cost estimate used here is based on the meta-analysis conducted in the HEIMTSA project; this new value has also been used in the most recent EU-wide assessment (Holland, 2014).

505

The cost of a hospital admission is partly based on the willingness to pay approach (WTP), as estimated by Ready et al. (2004). The WTP estimate takes into account three days in hospital care (because of a respiratory disease), and five days of bed rest at home. In addition to WTP, direct health care costs (three days) and lost work days (five days) contribute to the total cost of a hospital admission. The health care cost estimate used in the calculations corresponds to the mean cost of an acute care admission (< 90 days) in primary care in Finland. Original unit cost has been adjusted for the year 2017 using data from Statistics Finland on the temporal changes of health care costs in Finland.

510

515 The estimated cost of a working day in Finland originates from 2012. The value has been adjusted for
2017 using the labor cost index reported by Statistics Finland. The cost of a restricted activity day
consists of the cost of lost work days, and WTP costs of minor restrictions (symptoms) and more severe
restrictions (bed rest at home). The WTP values are based on Ready et al. (2004). For the working age
520 population, it was assumed that 25 % of the restricted activity days were spent in bed at home, 25 %
with symptoms at home, and 50 % at work with symptoms. Persons that are eligible for retirement (>
65 years, 25 % of the adult population) were assumed to spend 35 % of the restricted activity days in
bed and the rest suffering from symptoms.

525 We adjusted the unit costs for inflation, but not for the changes in the income levels, which is
accordance with the practice in the previous EU-wide assessment by Holland (2014). The WTP values
were selected according to Ready et al. (2004), in which the results have been reported in pounds in
1998. In this study, these have been converted to euros using the purchasing power parity index, and to
the values in 2017 using the Harmonised Index of Consumer Prices.

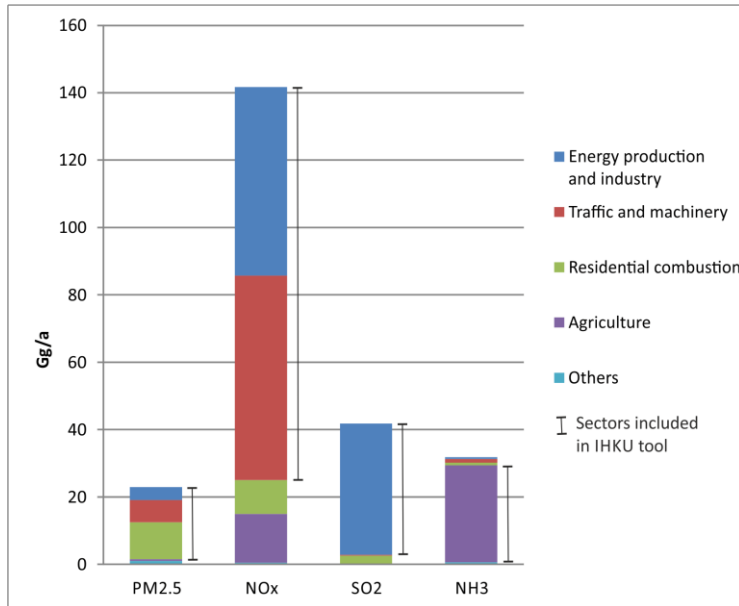
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3 Results

3.1 Summary of the emissions of PM_{2.5} and its main precursors in Finland

535 The total primary and main precursor emissions (for NO_x, SO₂ and NH₃) of PM_{2.5} in Finland in 2015
have been presented in Fig. 1. Regarding the primary emissions of PM_{2.5}, the most important domestic
pollution source categories were residential combustion (10.2 kt/a), and vehicular traffic and machinery
(6.6 kt/a). The energy production and industrial combustion units, and industrial processes were
responsible for smaller proportions of the primary emissions of PM_{2.5} (2.5 kt/a and 1.6 kt/a,
540 respectively).

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Fig. 1. The total amounts of the annual emissions in Finland in 2015 for the pollutants and source categories that were taken into account in this study (megatons/year). The NO_x emissions were defined as the sum of NO and NO₂, presented as the mass of NO₂. The vertical bars show the emission source categories that were included in the simplified web-based tool of assessment.

550

Regarding the emissions of nitrogen oxides, vehicular traffic and machineries, and the energy production and industry were the most important source categories. The emissions of sulphur dioxide were mostly originated from energy production and industry, and the emissions of ammonia mostly from the agricultural sector.

555

Karvosenoja (2008) has previously evaluated the uncertainties of the national annual average emission estimates of PM_{2.5} for residential combustion and vehicular traffic. The estimates of uncertainties included both those for the use of fuels and for emission factors. The uncertainties were estimated to range from - 36 % to + 50 % for residential combustion and from - 11 % to + 13 % for vehicular traffic, within 95 % confidence interval. The uncertainties of the emissions from point sources were found to be on the same level or lower as those for residential combustion. The uncertainties of the PM_{2.5} precursor emissions were on the same level or lower than those for the primary PM_{2.5} emissions.

560

Emissions from shipping have not been included in the above mentioned inventory. However, shipping emissions on a high resolution were used as input values in the SILAM model computations; described in more detail by Lehtomäki et al. (2018). The shipping emissions were provided by the computations using the STEAM emission model (e.g., Johansson et al., 2017).

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3.2 The modelled changes of spatial concentration distributions caused by the changes of emissions

575 The atmospheric dispersion, and the changes of concentrations caused by the reductions of emissions, were evaluated for (i) vehicular traffic, (ii) working and off-road machinery, and (iii) small-scale residential combustion. The analyses were made separately for urban and rural areas. In addition, in case of residential wood combustion, we assessed separately the dispersion originated from (i) fireplaces and sauna stoves, and (ii) recreational houses and the boilers of detached houses.

580

The computations were made partly using the FRES model, partly using the SILAM model. The FRES model was mostly used for evaluating the reductions of concentrations caused by primary emissions (i.e., the emissions of PM_{2.5}). We used the FRES model for this purpose, as the spatial resolution was finer, compared with the SILAM model computations. The SILAM model was used for evaluating the reductions caused by the emissions of pollutants that form secondary particulate matter in the atmosphere; the treatments of the FRES model do not include those processes.

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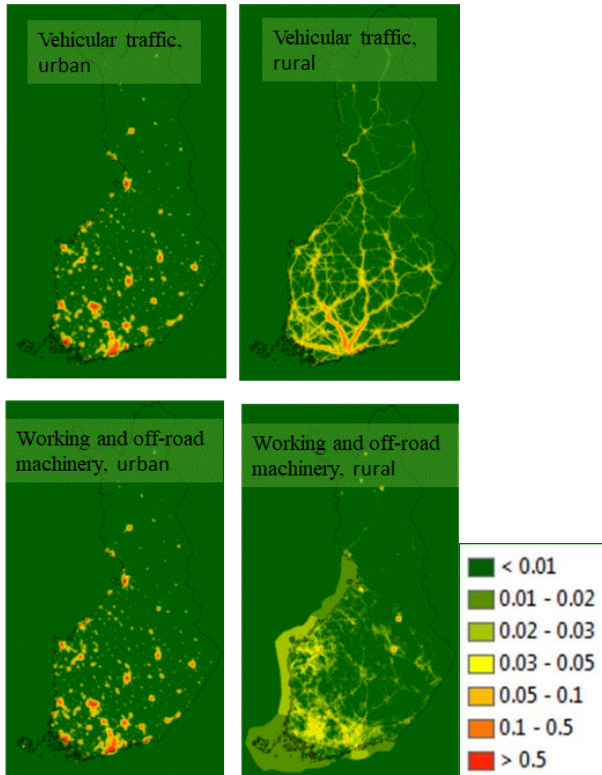
The considered secondary pollutants in the following results include the most substantial ones for each source category; we did not evaluate the impacts of the complete range of secondary pollutants. The secondary pollutants included NO_x originated from vehicular traffic and machineries, NH₃ from agriculture, and SO₂ and NO_x from power plants and industry. In addition, the SILAM model was used for evaluating the effects of the reductions of primary PM_{2.5} originated from power plants and industry; this was done to achieve a better consistency of the predicted results with regard to the two considered secondary pollutants for this source category.

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595

3.2.1 Vehicular traffic, working and off-road machinery, and residential wood combustion, evaluated using the FRES model

600 The predicted reductions of concentrations of PM_{2.5} are presented in Figs. 2a-d for vehicular traffic, and working and off-road machinery, separately for urban and rural areas. The computations were conducted using the FRES model on a spatial resolution of 250 x 250 m².



605

Figs 2a-d. The reductions of concentrations of $\text{PM}_{2.5}$ (ng/m^3), caused by a reduction of emissions of $\text{PM}_{2.5}$ by one ton. The results are presented for vehicular traffic (the upper panels), and working and off-road machinery (the lower panels). For both source categories, the changes in urban and rural areas are presented separately, in the left-hand side and right-hand side panels, respectively. The spatial resolution is $250 \times 250 \text{ m}^2$.

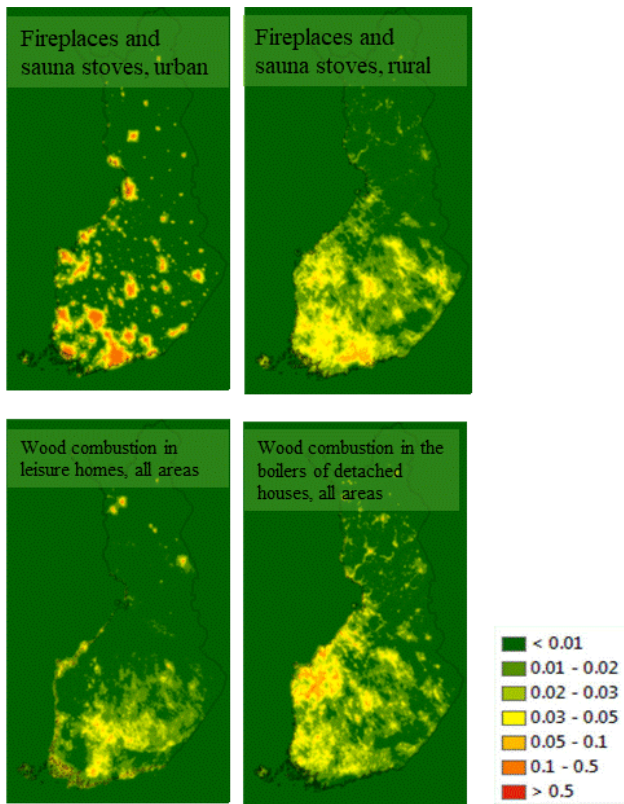
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As expected, the urban reductions were focused on the largest urban agglomerations, cities and towns, for both source categories. The rural vehicular reductions were focused on the main road and street network, especially in the most densely populated southern and western parts of the country. The machinery reductions were located within the most industrialized regions, most of which are located in south-western Finland; these were dispersed across a wider area, compared with the corresponding vehicular traffic reductions.

620

The predicted reductions of concentrations of $\text{PM}_{2.5}$ are presented in Figs. 3a-d for three segments of residential wood combustion. The reductions for fireplaces and sauna stoves are presented separately for urban and rural areas, whereas both the reductions in leisure homes and in the boilers of detached

houses are presented in one panel for the whole country. The computations were conducted using the
625 FRES model on a spatial resolution of 250 x 250 m².



630 Figs 3a-d. The reductions of concentrations of PM_{2.5} (ng/m³), caused by a reduction of emissions of
PM_{2.5} by one ton, originated from small-scale residential combustion. The changes due to the emissions
in fireplaces and sauna stoves are presented in the upper panels, and the changes due to the emissions
635 in recreational houses and in the boilers of detached houses are presented in the lower panels. For both
source categories, the changes in urban and rural areas are presented separately, in the left-hand side
and right-hand side panels, respectively. The spatial resolution is 250 x 250 m².

640 As expected, the urban reductions of the emissions for fireplaces and sauna stoves were focused on the
largest urban agglomerations. However, the urban reductions in leisure homes and in the boilers of
detached houses were much more evenly distributed. The reductions for leisure homes are expectedly
situated mostly in southern central Finland; this area has the most dense network of leisure homes. The

reductions from the boilers of detached houses are focused mostly in western Finland; this is caused by the differing cultural habits and preferences regarding housing in different parts of the country.

645

Kukkonen et al. (2018) has recently evaluated the uncertainties of the modelling system containing the urban scale UDM-FMI and CAR-FMI models. The model UDM-FMI was used for computing the source-receptor matrices within the FRES model. They evaluated the performance of the modelling system extensively, against the observations of PM_{2.5} concentrations during 16 years at five measurement stations in the Helsinki Metropolitan Area. The uncertainties of the predicted annual average concentrations of PM_{2.5} ranged from – 18 % to + 15 %.

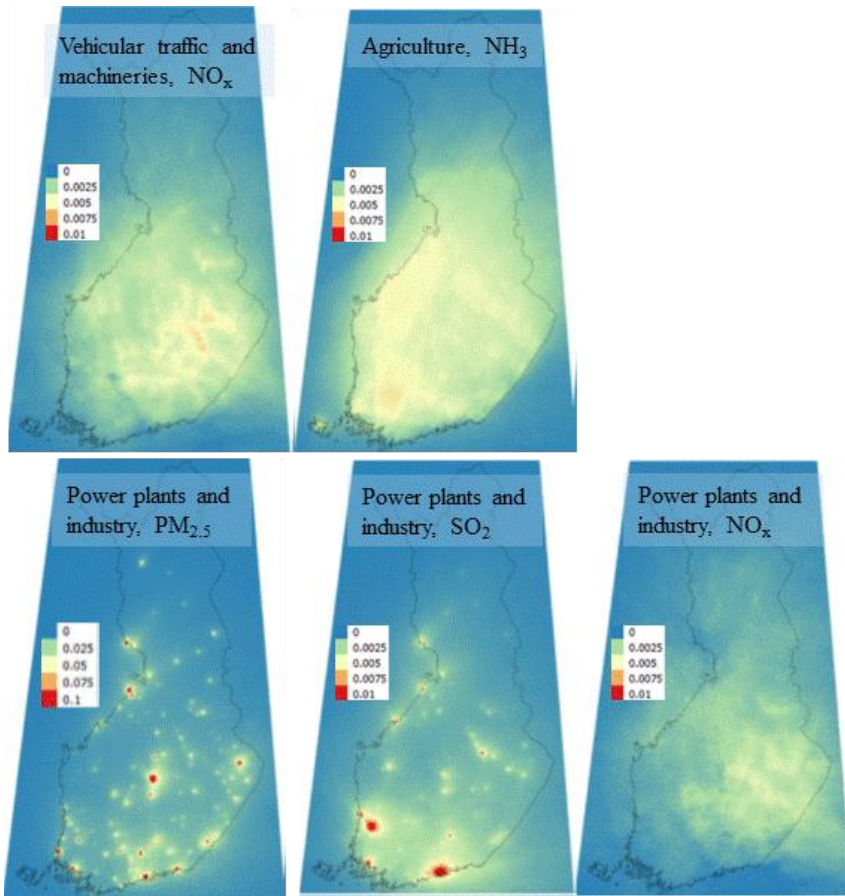
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3.2.2 Vehicular traffic, machineries, agriculture, and power plants and industry, evaluated using the SILAM model

655

The reductions of PM_{2.5} concentrations computed with the SILAM model are presented in Figs. 4a-e. The model grid covered entire Finland with a spatial resolution of 5 x 5 km².

660



665 Figs 4a-e. The reductions of concentrations of PM_{2.5} (ng/m³), caused by a reduction of emissions of one
 670 ton of corresponding pollutants, originated from three source categories. The panels present the
 decrease in concentrations due to reduction of the following emissions: (a) NO_x originated from
 vehicular traffic and machineries, (b) NH₃ originated from agriculture, (c) PM_{2.5} originated from power
 plants and industry, (d) SO₂ originated from power plants and industry, and (e) NO_x originated from
 power plants and industry. The spatial resolution is 5 x 5 km². The scale of reductions is different for
 the panel (c).

675 The most prominent PM_{2.5} reductions in the close vicinity of the emitting sources were caused by the
 decrease of primary emissions of PM_{2.5} originated from power plants and industry. A similar result was
 achieved for the PM_{2.5} reductions caused by SO₂ emission reduction; however, the absolute values of

the reduction were an order of magnitude smaller, compared with those caused by the PM_{2.5} emission reductions. This was caused partly by the fact that most of SO₂ is originated from relatively few major power plants and industrial regions, partly by the fairly slow chemical formation of sulphates.

680 The spatial patterns of the reduced PM_{2.5} concentrations were more homogeneously distributed over Finland in case of lowered emissions of the secondary pollutants NO_x and NH₃. This was caused by the relatively longer time scales of the relevant chemical reactions and by the geographical locations of the main sources of NO_x and NH₃, which are agricultural activities and vehicular traffic networks.

685 The predictions of the SILAM model have previously been extensively evaluated against monitoring data. For most cases, there has been fairly good or good agreement, with a slight underestimation of PM concentrations (Prank et al., 2016). Most recently, Lehtomäki et al. (2018) have evaluated the accuracy of the SILAM model for predicting the annual average concentrations of PM_{2.5}. The predicted annual average values were on the average 5 % lower than the observations at 37 stations in Finland in
690 2015.

3.3 The health impacts

695 The health impacts were evaluated based on the atmospheric dispersion computations addressed in the previous section. The impacts are presented in Table 3. The units of the values are different for the different columns. For instance, the values in the column ‘mortality’ are the numbers of the cases of premature deaths, and the values in the column ‘Lost life years’ are in years. The reported values are incremental health impacts, i.e., the presented impacts correspond to a unit amount (one kiloton) of
700 emissions. The values are therefore not the total health impacts within the country.

705 Table 3. The health impacts caused by an emission of one kiloton of PM_{2.5}, NO_x, NH₃, or SO₂ in Finland in 2015, for various domestic pollution source categories in various regions. Notation: e.g., “NO_x → secondary PM_{2.5}” refers to secondary fine particulate matter originated from the emissions of nitrogen oxides.

Pollution source category	Mortality (cases)	Lost life years (years)	Chronic bronchitis (cases)	Bronchitis (cases)	Cardiovascular admissions (cases)	Respiratory admissions (cases)	Work days lost (days)	Restricted activity days (days)
Road transport, primary PM _{2.5} , urban	108	660	118	305	49	54	41.7 10 ³	15.8 10 ³
Road transport, primary PM _{2.5} , non-urban	11	64	11	36	5	5	3.86 10 ³	1.46 10 ³
Non-road & machinery, primary PM _{2.5} , urban	132	823	146	357	60	66	52.1 10 ³	19.6 10 ³
Non-road & machinery, primary PM _{2.5} , non-urban	4	24	4	13	2	2	1.36 10 ³	0.53 10 ³
Residential houses, wood stoves and saunas, primary PM _{2.5} , urban	54	331	57	178	24	27	20.0 10 ³	7.63 10 ³
Residential houses, wood stoves and saunas, primary PM _{2.5} , non-urban	7	42	7	22	3	3	2.30 10 ³	0.90 10 ³
Recreational houses, wood stoves and saunas, primary PM _{2.5}	4	26	4	14	2	2	1.55 10 ³	0.60 10 ³
Residential houses, wood boilers, primary PM _{2.5}	9	56	9	31	4	4	3.16 10 ³	1.27 10 ³
Road transport, NO _x → secondary PM _{2.5}	1	4	1	2	0.3	0.3	0.22 10 ³	0.086 10 ³
Agriculture, NH ₃ → secondary PM _{2.5}	0.9	6	1	3.1	0.41	0.46	0.33 10 ³	0.13 10 ³
Industry and power plants, primary PM _{2.5}	7.2	44	7.5	23	3.19	3.50	2.63 10 ³	1.01 10 ³
Industry and power plants, SO ₂ → secondary PM _{2.5}	1	6	1.1	3.4	0.46	0.51	0.38 10 ³	0.15 10 ³
Industry and power plants, NO _x → secondary PM _{2.5}	0.4	2	0.4	1.1	0.15	0.17	0.12 10 ³	0.049 10 ³

710 In general, the impacts were largest in case of primary PM_{2.5} emissions, compared with those for the corresponding secondary pollution. As expected, the impacts in urban areas were also substantially larger than the corresponding impacts in non-urban areas. Regarding the pollution source categories, the most important were non-road and machinery, road transport in urban areas, and wood stoves and saunas in residential houses.

715 In addition to the above-mentioned health impacts, the infant mortality and the asthma symptoms were also considered. However, these impacts were negligible compared with other considered impacts. In case of the infant mortality, the background risk was very low, and for the asthma symptoms, both the prevalence and risk ratio were low. The infant mortality and asthma were therefore excluded from further analysis.

725 The uncertainty of the health effect values can be estimated based on the adopted concentration-
response functions. The majority of the public health costs are related to premature mortality. We
therefore address here the average concentration-response for the PM_{2.5} related to mortality, which has
been assumed to be 1.062 (cf. Table 1), with a linear dependency with respect to the concentration. The
95 % confidence limits of this value range from 1.040 to 1.083. We therefore conclude that the lowest
730 and highest health effect estimates (within the 95% confidence interval) could be approximated by
multiplying by the predicted health effect values by 0.65 (i.e., 4.0 % / 6.2 %) and 1.3 (8.0 % / 6.2 %).

3.4 The economic impacts

735 We have assessed the economic impacts of the selected potential PM_{2.5} emission reductions, based on
the health impacts addressed in the previous section. These have been computed for a change of one
ton of the annual emissions for the selected pollutants in 2015. The results include only the impacts of
the Finnish emissions to the population in Finland; i.e., the health impacts caused by the Finnish
emissions in other countries have not been evaluated.

740 First, the estimated contributions to the total costs were evaluated for the various health outcomes. The
detailed results of these computations are presented in Appendix A. The mortality effects were clearly
the largest factor affecting the total costs. However, also the costs associated with restricted activity
days, lost working days and chronic bronchitis were found to be substantial.

745 The final results of the economic cost computations are presented in Table 4. The values in Table 4
have been presented for three alternative options for computing the economic impacts: (i) the average
value of life year (VOLY), assumed to be equal to 160 000 €, (ii) the median value of life year,
assumed to be 69 000 €, and (iii) the average value of statistical life (VSL), assumed to be 2.65 million
€.

750 The results have been presented separately for the source categories that have relatively lower and
higher emission heights, respectively. The latter category includes the industrial pollution sources and
power plants. The results have also been presented in terms of the pollutant, the emissions of which
have been assumed to be decreased; these include both primary PM_{2.5} and the main precursor
755 substances. For the most significant source categories and substances, the results have also been
presented separately for various types of areas, such as the urban and rural areas. For the primary PM_{2.5}
emissions from industry and power plants, the results were presented separately for areas with different
population densities; these included the capital area, and relatively more and less densely populated
municipalities, respectively.

760 There are substantial variations of the results, depending on the economic computation methods
(average or median VOLY or VSL). However, the order of these results is the same for all the results;
e.g., the computation using VSL results in the highest economic values. We have therefore illustrated
the results computed with one of these methods, i.e., the average of VOLY, in Figs. 5a-b and 6a-b.
765 These figures therefore can be used to illustrate the relative economic benefits of the selected emission
reduction alternatives.

The economic benefits are clearly largest for the emission reductions for the source categories that have
low emission heights (Figs. 5a-b), compared with those with substantial emission heights (Figs 6a-b).

770 For both kinds of source categories, the reductions expectedly result in higher public health benefits in
the more densely populated regions. For instance, the reductions of the PM_{2.5} emissions originated
from vehicular traffic, non-road and machinery and residential wood combustion in urban areas result
in approximately an order of magnitude higher economic benefits, compared with the impacts of the
775 corresponding emission reductions in rural areas. The results also show that the reduction of the
precursor emissions of PM_{2.5}, such as NO_x, NH₃ and SO₂ was clearly less effective for reducing both
the PM_{2.5} concentrations and the adverse economic impacts, compared with reducing directly the
emissions of PM_{2.5}.

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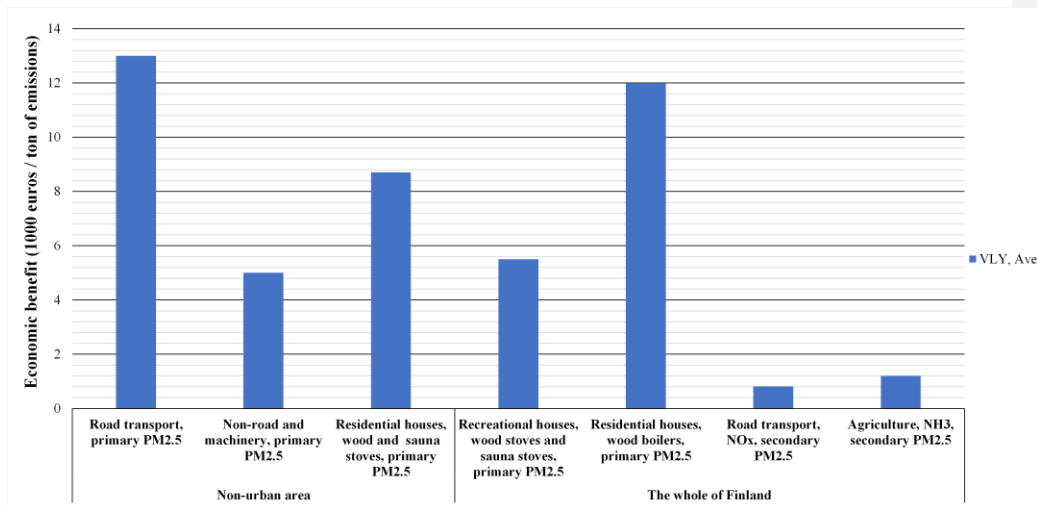
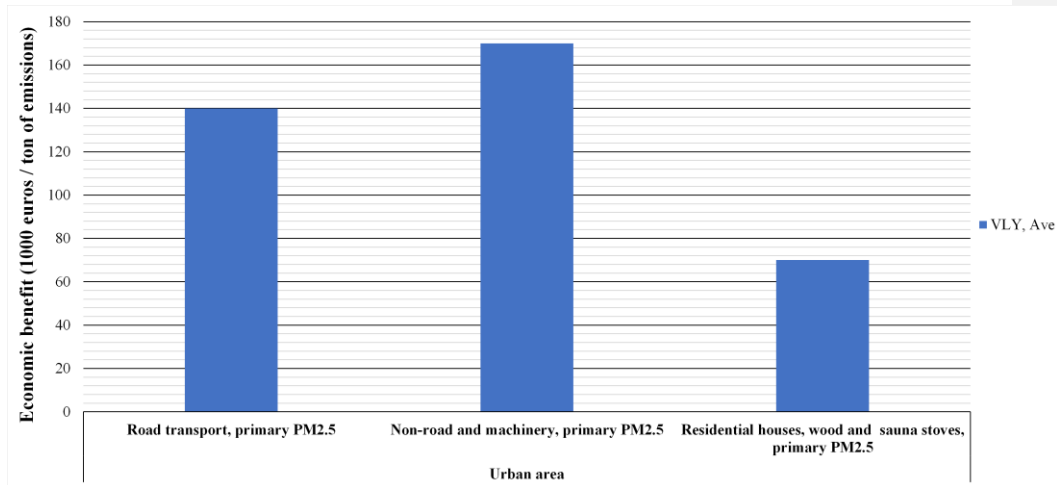
780 The uncertainties of the economic evaluations can be estimated based on the difference of the three
alternative methods, i.e., those based on the average and median VOLY, and the one based on the
average VSL. Assuming that the average VOLY would be the base value (denoted here as 1.0), the
uncertainty of this estimate would range from 0.57 to 2.2.

785

Table 4. Economic benefits obtained by the assumed reductions of emissions, in thousand euros per ton of emissions. The results are presented for the various source categories, in various domains. The first presented value has been computed based on the average value of life year, and the two values in parenthesis based on the median value of life year and the average value of statistical life, respectively.

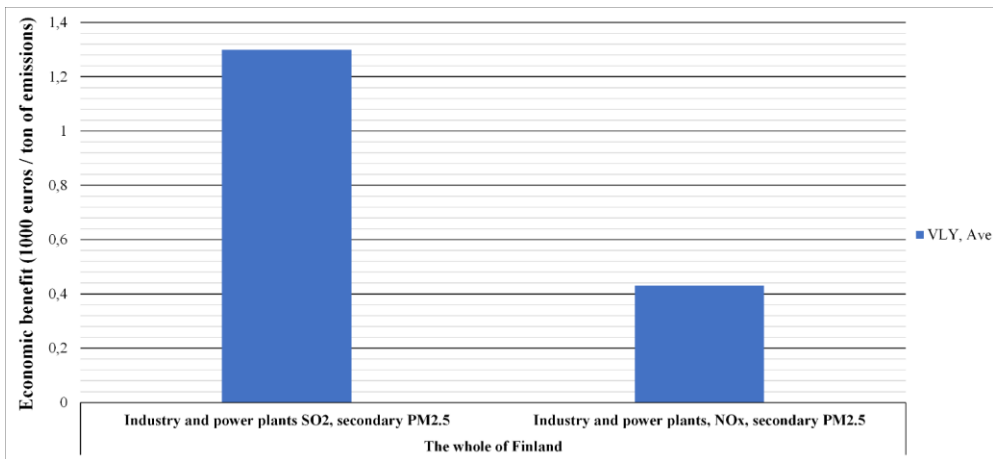
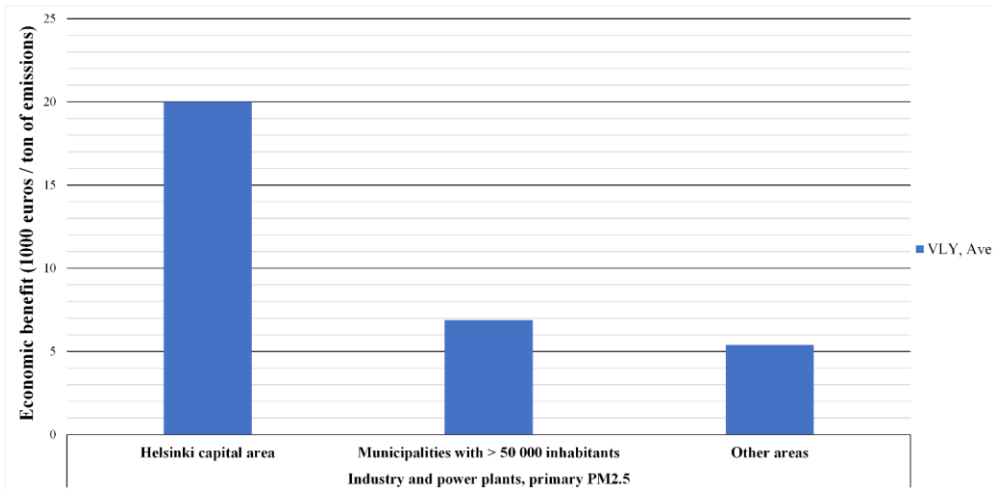
Source category and the emission height	Region, in which the reduction of emission takes place		
	Urban area	Non-urban area	
Emissions at low height			
Road transport, primary PM _{2.5}	140 (80–320)	13 (7.6–31)	
Non-road and machinery, primary PM _{2.5}	170 (100–390)	5.0 (2.8–11)	
Residential houses, wood and sauna stoves, primary PM _{2.5}	70 (40–160)	8.7 (4.8–19)	
	Whole of Finland		
Recreational houses, wood stoves and sauna stoves, primary PM _{2.5}	5.5 (3.1–13)		
Residential houses, wood boilers, primary PM _{2.5}	12 (6.6–27)		
Road transport, NO _x emissions forming secondary PM _{2.5}	0.82 (0.46–1.8)		
Agriculture, NH ₃ emissions forming secondary PM _{2.5}	1.2 (0.70–2.8)		
Emissions at substantial height	Helsinki capital area	Municipalities with > 50 000 inhabitants	Other areas
Industry and power plants, primary PM _{2.5}	20 (11–44)	6.9 (3.9–16)	5.4 (3.1–12)
	Whole of Finland		
Industry and power plants SO ₂ emissions forming secondary PM _{2.5}	1.3 (0.73–3.1)		
Industry and power plants, NO _x emissions forming secondary PM _{2.5}	0.43 (0.24–1.0)		

800



805 Figs 5a-b. Economic benefits obtained by the assumed reductions of emissions, in thousand euros per
 ton of emissions, for sources having a low emission height. The results are presented for urban areas
 (upper panel, a), and for non-urban areas and for the whole country (lower panel, b) in case of various
 source categories and pollutants, in various domains. All the values correspond to the computations
 using the average value of life year.

810



815 Figs 6a-b. Economic benefits obtained by the assumed reductions of emissions, in thousand euros per
 ton of emissions, for sources having a high emission height. These results are presented for industry
 and power plants. The upper panel (a) presents results for the emission reductions of PM_{2.5} for various
 geographic regions, and the lower panel (b) for the emission reductions of SO₂ and NO_x for the whole
 of Finland. All the values correspond to the computations using the average value of life year.

820

3.4 An open access tool of assessment for evaluating the economic impacts

825 We have also designed and implemented a user-friendly internet-based tool of assessment for
evaluating the health costs of various assumed emission reduction options. This tool was designed to
facilitate an easy use of the model to policy makers, stakeholders and environmental experts. The tool
can be accessed via a user-friendly interface in the internet
830 (<https://www.ymparisto.fi/IHKU/haittakustannuslaskuri/>). This calculator is based on the numerical
results of this study (such as those presented in Table 4); however, some minor simplifications were
made regarding the included emissions. The included emission source categories have been presented
by the vertical bars in Fig. 1.

The internet-based tool requires as input value the amount of reduced emissions (tons/year) for a source
835 category, pollutant and region, corresponding to a selected abatement measure, bundle of measures or
strategy. The tool can then be used to compute as output the annual financial benefits of the measure or
strategy (in euros), presented both tabulated and graphically. For instance, if the policy maker has an
estimate of (i) the emission reduction that could be achieved by a potential abatement measure and (ii)
840 the economic cost of implementing the measure, he or she can use the tool to analyze whether the
measure would result in more substantial economic benefits, compared with the costs. Clearly, the tool
could also in such a case be used for comparing the cost-effectiveness of alternative potential emission
reductions.

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845 4 Conclusions

We have presented an integrated tool of assessment for evaluating the public health costs of fine
particulate matter (PM_{2.5}) in ambient air. The atmospheric dispersion was analyzed both using a
850 chemical transport model (SILAM) and a decision-support tool that uses source-receptor matrices
(FRES). The model was applied to analyze the costs of the domestic primary and precursor emissions
of PM_{2.5} in Finland in 2015. The model does not address other effects of fine particulate matter in
ambient air, such as, e.g., the impacts on climate change and on the state of the environment.

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We have evaluated the national emissions on a fine spatial resolution, 250 x 250 m² for the whole
855 country. The concentrations were computed using either the same resolution as the emissions (using the
FRES model), or on a resolution of 5 x 5 km² (the SILAM model) over the whole of Finland. Such fine
resolutions have not previously been used for a geographically extensive area. In the assessments of
public health costs, the concentrations have commonly been predicted on spatial resolutions of tens of
860 kilometers (e.g., Heo et al., 2016).

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It has previously been highlighted (Karvosenoja et al., 2011, Korhonen et al., 2019) that the modelled
865 exposure values are sensitive to adopted spatial grid resolutions. The predicted exposure values were
substantially lower for computations with a coarser spatial resolution. More specifically, Karvosenoja
et al. (2011) demonstrated that using a finer spatial resolution, 1 x 1 km² instead of 10 x 10 km², resulted
in an increase by an order of magnitude of the modelled population weighed concentration attributed
by traffic emissions. It is therefore essential to use a sufficiently fine model resolution in view of the

870 assessment of health impacts. This is especially important for primary particles from emission sources at low emission heights.

875 Regarding the health costs of fine particulate matter, it is important also to allow for the precursor emissions. The present study has explicitly considered the health costs related to the PM_{2.5} precursor emissions, on a finer spatial resolution (5 x 5 km²) than previous studies. Muller and Mendehlson (2009) and Heo et al. (2016) have also allowed for the impacts of PM_{2.5} precursors on the health costs in the U.S.; Heo et al. (2016) adopted a resolution of tens of km. The present study has also modelled in detail the organic fraction of fine particulate matter; this fraction has been neglected in most previous studies on public health costs.

880 The health and economic impacts were analyzed based on the most significant health outcomes. The risk ratios and economic evaluations were based on the most recent results in the literature. However, reliable concentration-response functions were available only for a limited number of health outcomes. For example, the effects of the long-term exposure on the cardiorespiratory and cancer morbidity could not yet be included in the model, although these can be associated with substantial health care and willingness to pay costs. The economic costs of the PM_{2.5} exposures have therefore probably been under-predicted in this respect.

890 There are also substantial uncertainties in quantifying the economic effects of the various health outcomes. In particular, the final estimates of the economic costs substantially depend on the selection of the economic measures; these can alternatively be the value of life year, either as an average or a median, or the value of statistical life. We have therefore presented three potential values for each public health cost, for each source category and pollutant.

895 The total uncertainties of the adopted impact pathway approach can be analyzed by studying the uncertainties for each of the stages of the assessment. The largest uncertainties to the final cost estimates were caused by the health impact assessments and the economic evaluations. We evaluated that the lowest and highest health effect estimates (within the 95% confidence interval) ranged from 0.65 to 1.3 (when the predicted optimal evaluation is normalized to 1.0). Similarly, the uncertainty of the economic cost estimate was found to range from 0.57 to 2.2. The uncertainty of the assessment resulting from these two main sources of uncertainty would therefore vary approximately from 0.36 to 2.9.

900 The developed modelling system can be used to evaluate the costs of the health damages for various emission source categories, for a metric ton of emissions of PM_{2.5}. The economic benefits were clearly largest for the emission reductions for the source categories that have low emission heights, such as vehicular traffic, non-road and machinery, and residential wood combustion. For all source categories, the emission reductions provided substantially higher health benefits, even by an order of magnitude, in the urban areas, compared with those in rural areas. The reduction of the precursor emissions of PM_{2.5} resulted in clearly lower health benefits, compared with reducing directly the emissions of PM_{2.5}.

910 This study has addressed outdoor concentrations for a stationary population. The so-called dynamic exposure modelling is a promising new research direction that addresses also the movements of the population in various micro-environments, and the infiltration of pollution to indoor air. Using the dynamic approach, also indoor pollution sources and sinks could in principle be taken into account.

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925 The dynamic exposure modelling has been applied, e.g., for Helsinki (e.g., Kousa et al., 2002, Soares et al., 2014, Kukkonen et al., 2016) and for London (Smith et al., 2016, Singh et al., 2019). However, performing such modelling for an entire country would be challenging.

Based on the results achieved in this study, we have designed an open-access, user-friendly web-based tool of assessment. Both the final results obtained in this study, and the web-based assessment tool can be used in analyzing the economic benefits associated with various alternative abatement measures, policies or strategies. If the user of the assessment tool will also know the economic costs of the planned alternative measures, he or she can inter-compare the cost-efficiency of different potential emission mitigation measures and strategies.

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935 5. Code and data availability

The SILAM code is publicly available.

The emission data, and the predicted concentration data used in this study is available, by contacting the responsible authors, i.e., N. Karvosenoja, J. Kukkonen and M. Sofiev.

940 6. Acknowledgements

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Appendix A. Public health costs for various health outcomes

Table A1. Public health costs in euros of one ton of source-specific PM_{2.5} emissions for various health outcomes in Finland in 2015. Notation: VOLY = value of life year, VSL = value of statistical life. The values have been presented using three significant numbers.

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Emission source category, pollutant and the region	Mortality, 10 ³ VOLY average	Mortality, 10 ³ VOLY median	Mortality, 10 ³ VSL average	Chronic bronchitis	Bronchitis	Cardiovascular admissions	Respiratory admissions	Work days lost	Restricted activity days
Road transport, primary PM _{2.5} , urban	106	45.5	286	7590	239	139	152	10600	15800
Road transport, primary PM _{2.5} , non-urban	102	4.42	27.8	702	28	13	15	982	15800
Non-road & machinery, primary PM _{2.5} , urban	132	56.8	349	9420	280	171	187	13200	19600
Non-road & machinery, primary PM _{2.5} , non-urban	3.84	1.66	10.2	252	10	5	5	346	527
Residential houses, wood stoves & sauna, primary PM _{2.5} , urban	53.0	22.8	143	3660	139	69	76	5080	7630
Residential houses, wood stoves & sauna, primary PM _{2.5} , non-urban	6.72	2.90	17.4	429	18	8	9	583	900
Recreational houses, wood stoves & sauna, primary PM _{2.5}	4.16	1.79	11.4	287	11	5	6	394	601
Residential houses, wood boilers, primary PM _{2.5}	8.96	3.86	24.4	601	24	11	13	803	1270
Road transport, NO _x →secondary PM _{2.5}	0.64	0.28	16.4	41	2	1	1	55	86
Agriculture, NH ₃ →secondary PM _{2.5}	0.96	0.41	2.50	62	2	1	1	85	131
Industry&power plants, primary PM _{2.5}	7.04	3.04	19.1	483	18	9	10	667	1010
Industry&power plants SO ₂ →secondary PM _{2.5}	0.96	0.41	2.77	70	3	1	1	97	146
Industry&power plants, NO _x →secondary PM _{2.5}	0.32	0.14	0.93	23	1	0	0	31	49

8. Author contributions

1305 Jaakko Kukkonen has compiled and written a substantial part of the article. N. Karvosenoja, T. Lanki
and J. Kukkonen have proposed this study for funding and written a research plan. M. Savolahti, V.-V.
Paunu and N. Karvosenoja have done the emission and dispersion computations with the FRES model,
part of the economic computations, compiled a substantial fraction of the results together, and written
1310 part of the article. Y. Palamarchuk and M. Sofiev have conducted the SILAM computations and written
the corresponding parts of the article. T. Lanki and P. Tiittanen have conducted the health impact
assessments. V. Nurmi has done part of the economic computations, contributed to the section on
economic assessments, and written a substantial part of the literature review in the introduction. L.
Kangas and A. Karppinen have compiled the required meteorological information and evaluated the
dispersion matrices for the FRES model. Ms. A. Maragkidou has post-processed the data and
1315 contributed to the writing of the literature review and other parts of the article.

9. Competing interests

The authors declare that they have no conflict of interest.

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