# Computational analysis of source receptor air pollution problems

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**Abstract**

This study introduces a method of graph computing for Environmental Economics. Different visualization modules are used to reproduce source-receptor air pollution schemes and identify their structure. Data resources are emissions-depositions tables, available online from the European Monitoring and Evaluation Program (EMEP) of the Long-Range Transmission of Air Pollutants in Europe. In network models of pollutants exchange, we quantify the responsibility of polluters by exploring graph measures and metrics. In a second step, we depict the size of the responsibility of EU countries. We create pollution schemes for ranking the blame for the change in pollutants in the extended EMEP area. Our approach considers both the activity and the amount of pollution for each polluter. To go a step further in qualitative analysis of pollution features, we cluster countries in communities, bonded with strong polluting-based relationships. The network framework and pollution pattern visualization in tabular representations is integrated in Mathematica computer software.

**Keywords**: Computational data analysis; graph modeling; visual analytics; source-receptor air pollution; polluters' responsibility.

**JEL Codes**: C63; C88; P28; Q51; Q53; Q58.

## 1. Introduction

This study proposes a new method of graph computing in Environmental Economics. Specifically, it discusses methods of scientific data processing, scientific visualization and visual analytics for data sources coming from yearly country-to-country source-receptor (**SR**) matrices for the extended European Monitoring and Evaluation Program (hereafter EMEP) domain. Data for air pollution transfers are produced by model runs driven by ECMWF-IFS meteorology and are presented in 44×44 up to 49×49 matrices (EMEP report 2016, appendix C; Colette et al., 2016). The source-receptor tables are calculated for the meteorological and chemical conditions of each year (here 2010 SR matrices are analyzed, source: EMEP Status Report 1/2012). The source-receptor (SR) relationships give the change in air concentrations or depositions resulting from a change in emissions from each emitter country.

We analyze SR pollutants from an emitter country (source) to itself and to other countries within EMEP domain (receptors). We propose a way to investigate the responsibility for the change in depositions of:

- Oxidised Sulphur (OxS). The contribution from SOx, NOx, NH3 and VOC have been summed up and scaled to a 100% reduction. Units: 100 Mg of S.
- Oxidised Nitrogen (OxN). The contribution from SOx, NOx, NH3 and VOC have been summed up and scaled to a 100% reduction. Units: 100Mg of N.
- Reduced Nitrogen (NHx). The contribution from SOx, NOx, $NH_3$ and VOC have been summed up and scaled to a 100% reduction. Units: 100Mg of N.

Also, we investigate the responsibility for the change in air concentrations of PM (PM conc):

- PM2.5. Effect of a 15% reduction in PPM emissions. Units: $ng/m^3$
- PM2.5. Effect of a 15% reduction in SOx emissions. Units: $ng/m^3$
- PM2.5. Effect of a 15% reduction in NOx emissions. Units: $ng/m^3$
- PM2.5. Effect of a 15% reduction in NH3 emissions. Units: $ng/m^3$
- PM2.5. Effect of a 15% reduction in VOC emissions. Units: $ng/m^3$

Pollution responsibility includes domestic emissions (self-pollution) and transboundary exports. Our computerized approach generates visual data representations and develops a causal analysis for emission flows based on images.

We take into consideration both activity and strength for each emitter. In particular, we

i. quantify countries' responsibility for pollution, weighting two factors: the dispersion of the emissions over the receptor countries and the deposition levels coming from each emitter country
ii. indicate the top polluting countries in self-evident visual schemes
iii. present graphically countries' polluting acts, for each pollutant separately
iv. ranking of countries with respect to their responsibility for pollution

Our computer codes[1] offer reproducible visualization and data analysis for the changes in depositions of main pollutants (SOx, NOx, reduced nitrogen) and PM concentrations (PM2.5, PM2.5_SOx, PM2.5_NOx, PM2.5NH3, PM2.5NMVOC). Providing our results, reasoning decision making aimed at effectively controlling emissions is possible (Halkos 1992, 1993, 1994, 1996; Hutton and Halkos 1995). Computing is made in Mathematica's environment where data visualization modules are employed. Graph construction and graph metrics is our theoretical and methodological basis. In previous studies, the authors applied computer algebra

[1] A Mathematica implementation is available on request

system (CAS) approaches to study environmental economics problems (Halkos and Tsilika 2014, 2016, 2017).

This paper consists of six sections. Section 2 presents first the basic terminology and then introduces the concepts and notions of graph theory that are used in our environmental economic analysis. In section 3 we create a series of networks computed from 2010 SR pollution data for countries inside the EMEP area as reported in the source-receptor tabular information in the EMEP/MSC-W website[2]. The polluters' responsibility is illustrated and a comparison of the variations of responsibility is made over different pollutants. In section 4, gray-shaded tabular snapshots depict the spatial distribution of SR pollutants. Our visual approach can start a conversation about which are the predominant sources of air pollution, where measures for the reduction of emissions should be taken, which countries to penalize. Section 5 investigates which countries are bonded with intense polluting actions and are closely related in the global pollution feature. We conclude by discussing the relevance of our results with respect to policy making and potential economic consequences.

## 2. Basic concepts and the methodological approach

Graphs are made up of vertices (also called nodes) and edges. A graph with weights assigned to its edges is a weighted graph. A graph G={V,E} consists of a set of vertices V and a set of edges E. Each vertex V stands for a country/area. Edges E depict the polluting interaction from one country to another. Outcoming edges $E_{out}$ represent emitters' output and incoming edges $E_{in}$ represent receptors' input. The weights used are the levels of SOx depositions. In this conceptual direction, country-

[2] All the data are available from the EMEP database (http://emep.int/mscw/index_mscw.html)

to-country blame matrices for the change in the value of each pollutant can be illustrated as country-to-country blame networks.

In our analysis we shall focus on the number, strength and the structural model of their connections. Graphs and networks provide a structural model that makes it possible to analyze and understand how many separate emitters act together within a common pollution feature. Our input data was the SR matrices, where we have substituted the negative values with zeros, as a negative change in depositions is equivalent to a null contribution from the emitter country[3]. We indicatively present the $SO_x$ deposition network for 2004 in Figure 1.

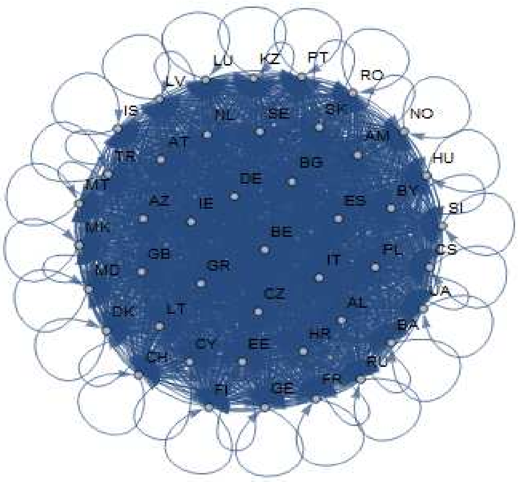



**Figure 1**: The exchange of depositions of OXS among 44 countries in 2004

In order to evaluate nodes' importance in weighted networks, three centrality measures are employed, including degree centrality and node strength. Degree centrality and node strength are well-known graph measures (see indicatively Freeman, 1979; Everett and Borgatti, 2005; Borgatti, 2005; Borgatti and Everett, 2005; Borgatti and Everett, 2006); the third centrality measure is introduced by Opsahl et al. (2010) and is referred to as "generalized degree centrality".

[3] In our analysis we do not consider the negative values. Future extension will be the consideration of the negative values and their impact on the responsibility allocation.

The degree centrality $C_D$ of a given node $i$ is formalized as follows

$$k_i = C_D(i) = \sum_{j}^{N} x_{ij} \tag{1}$$

where $j$ represents all other nodes, $N$ is the total number of nodes and $x$ is the adjacency matrix in which the cell $x_{ij}$ is defined as 1 if node $i$ is connected to node j and 0 otherwise (Opsahl et al., 2010).

Node strength $C_D^w(i)$ sums up the weights of the edges of a given node $i$, as given next

$$s_i = C_D^w(i) = \sum_{j}^{N} w_{ij} \, , \tag{2}$$

where $w_{ij}$ is an entry of the weighted adjacency matrix; $w_{ij}$ is the weight of a directed edge from node $i$ to node $j$. If there is no edge the weight is taken to be 0.

A node (emitter) with numerous outcoming edges (carrying any weight) has a high $k_i$. In the environmental context we set, the interpretation of this result is that it constitutes an environmental threat, in the sense that exposes many receptor countries to the harmful effects of country-to-country air pollution. In addition, an active emitter makes recipients take precautionary measures to deal with the negative environmental outcome. A node (emitter) with outcoming edges carrying large weights has a high $s_i$; such a node constitutes a major polluter.

The generalized degree centrality measure constitutes a hybrid formulation combining the two former concepts of centrality. In this measure both node activity and node strength are taken into consideration. Following Opsahl et al. (2010) we have

$$C_D^{w\alpha}(i) = k_i \times \left(\frac{s_i}{k_i}\right)^{\alpha} = k_i^{\,1-a} \times s_i^{\,a} \, , \tag{3}$$

and if considering solely outgoing edges

$$C_{D-out}^{w\alpha}(i) = k_i^{out} \times \left( \frac{s_i^{out}}{k_i^{out}} \right)^{\alpha} = k_i^{out(1-a)} \times s_i^{a}, \qquad (4)$$

where $\alpha$ is a positive parameter that can be set according to research setting and data.

In our analysis, we use node degree, node strength and generalized degree centrality, as defined in (1), (2) and (4) respectively, to quantify polluters' responsibility. For generalized degree centrality estimation we assign to parameter $\alpha$ the value of 0,8, weighting the magnitude (amount) of pollution with 0,8 and the dispersion of pollution with 0,2 for each emitter country. The resulting indicators aim to identify the most "dangerous" or most "threatening" emitters or the emitters which systematically defy protocols and conventions/regulations (Economic Commission for Europe 2013; UN-ECE 1998).

## 3. Polluters responsibility

Figures 2-4 present pollution schemes for the year 2010 for SR pollutants and highlight how polluting countries contribute to the change of depositions of main pollutants or PM concentrations, in the EMEP domain. Following the analysis made in section 2, the responsibility of a country is quantified by centrality indices and is illustrated by the size of the node associated to the country; the larger the node is the larger contribution the country has in the amount and/or the dispersion of the pollution.

Measuring responsibility with generalized degree centrality, figures 2a,b,c reveal a pollution feature with Russian Federation (extended), Kazakhstan (extended), Ukraine, Turkey, Germany, France (RUE, KZT, UA, TR, DE, FR) taking the bigger polluter's responsibility for depositions of SOx, NOx, RDN (see also appendix II). Concerning the air concentrations of PM, different pollution features are formed, as significant polluting acts appear in numerous countries. Figures 2d-h indicate that pollution responsibility is shared among many countries.

Figures 3 and 4 illustrate polluters' responsibility using node strength and degree centrality correspondingly.

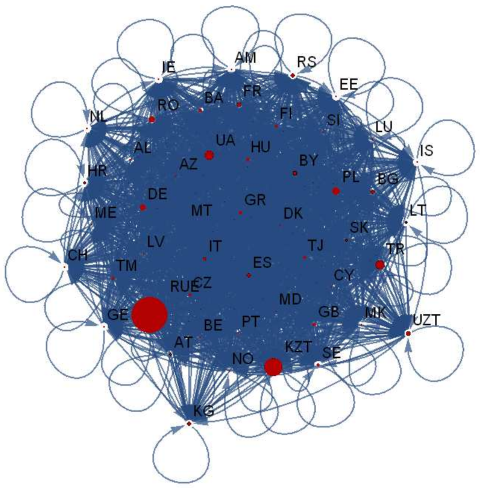
## 4. Tabular representation of significant SR data

To gain a different insight of the same data, we process through a module for visualization of tabular data that ignores connection lines and looks only at depositions' (or air concentrations) amount, origin and destination. The source-receptor interaction scheme is illustrated[4] in the graphics of Figure 5. The SR tables are filtered with pollutant quantity (level) in order to indicate the major pollution effects in the pollution tabular scheme. Tabular representations succeed to illustrate the dispersion of pollution within the EMEP domain.

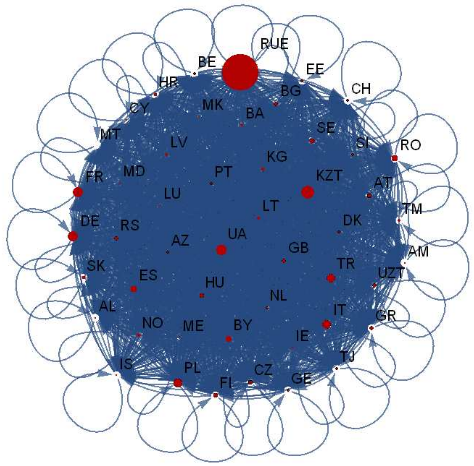
As the entries of the deposition tables vary considerably from country to country, only large values are visible (being more environmentally significant). Matrix cells with different shades of gray show the change in the amount of the pollutant for each receiver country (Figure 5). The color rule says that a white cell states no change in the pollutant; grey-shaded cells signify changes of variant degrees. A dark shade is related to a high deposition/concentration of pollutant and pinpoints an intense pollution effect. Very dark colored to black cells mark the peaks in levels of the relevant pollutant.

[4] Visual representations of matrices are generated by `ArrayPlot` Mathematica function

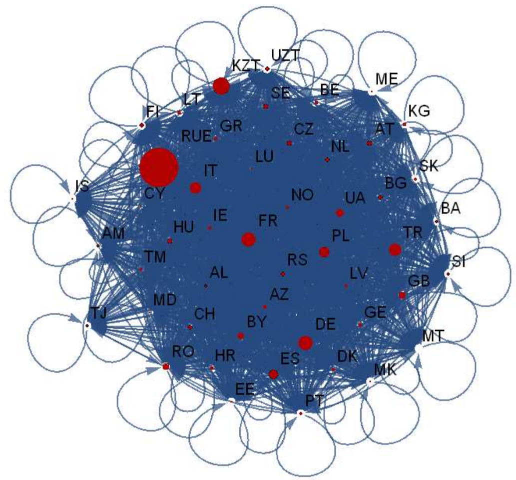
Country/region codes are explained in Appendix I. Analytical results sorting countries according to the selected pollution indicator can be found in Appendix II.



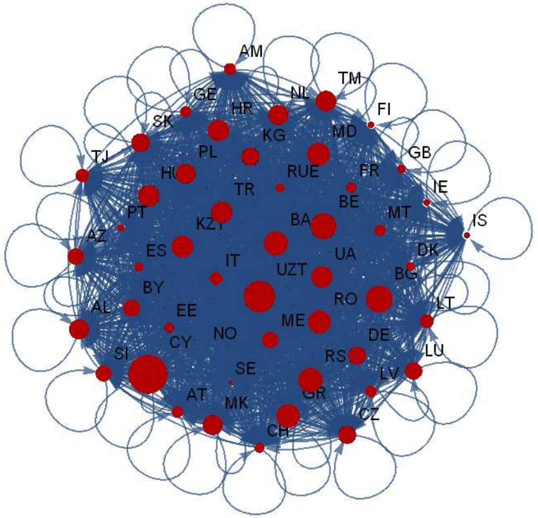
(a) Visualizing polluters' responsibility into 2010 country-to-country blame network for **SOx** deposition
(Russian Federation (extended) - RUE is the main polluter)



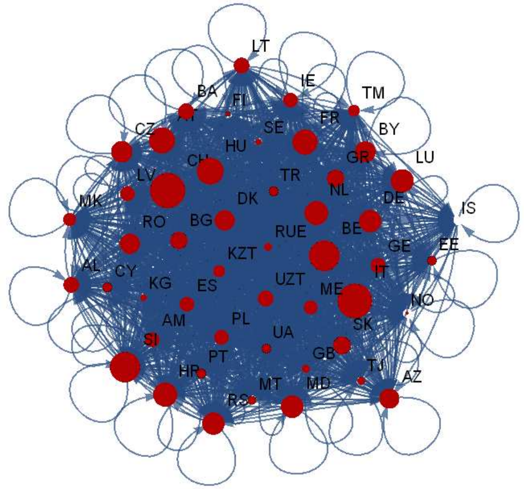
(b) Visualizing polluters' responsibility into 2010 country-to-country blame network for **NOx** deposition
(Russian Federation (extended) - RUE is the main polluter)



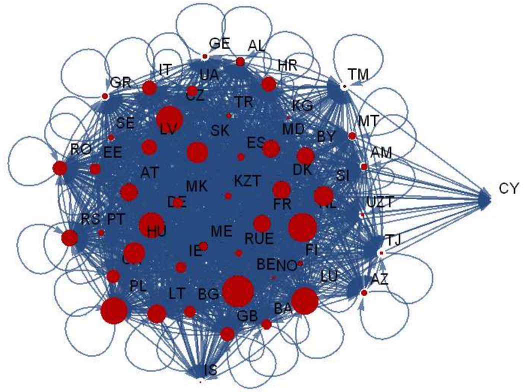
(c) Visualizing polluters' responsibility into 2010 country-to-country blame network for **reduced nitrogen** deposition
(Russian Federation (extended) - RUE is the main polluter)



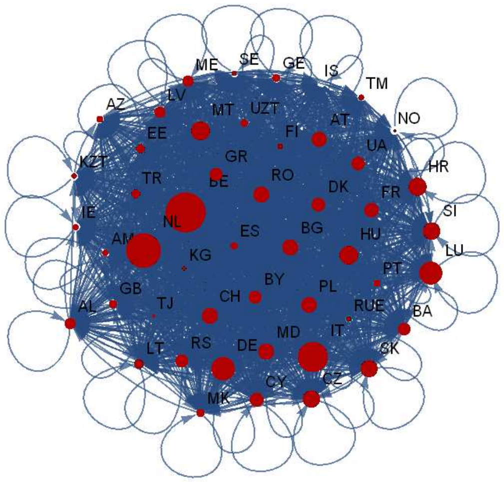

(d) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_SOx** (Cyprus - CY is the main polluter)



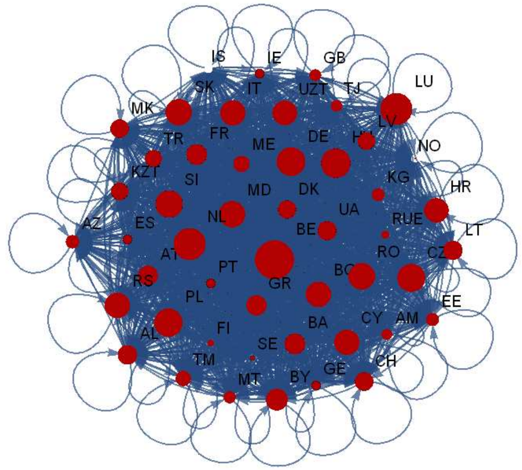

(e) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NOx** (Switzerland - CH is the main polluter)




(f) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NH3** (Belgium - BE is the main polluter)

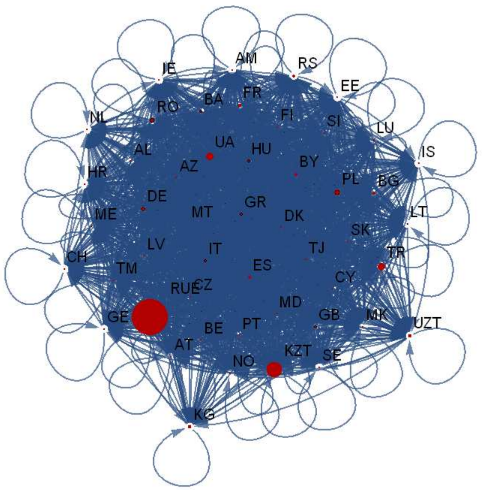



(g) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NMVOC** (Belgium - BE is the main polluter)

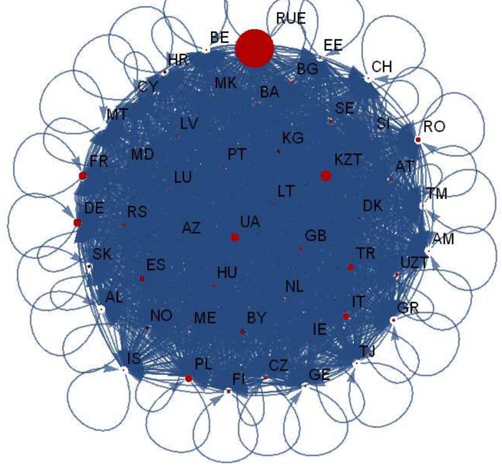



(h) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5** (Belgium - BE is the main polluter)

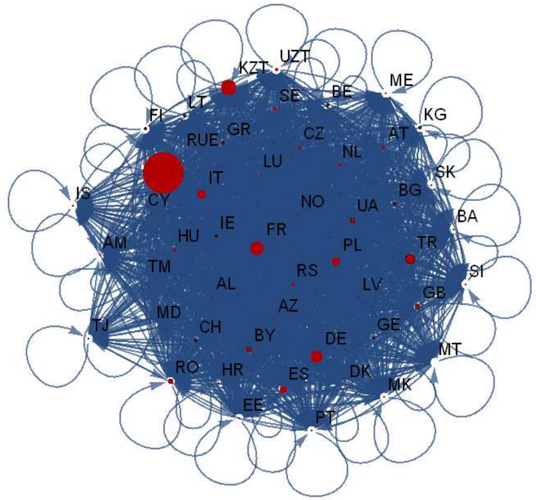
**Figure 2**: Responsibility is quantified by generalized degree centrality



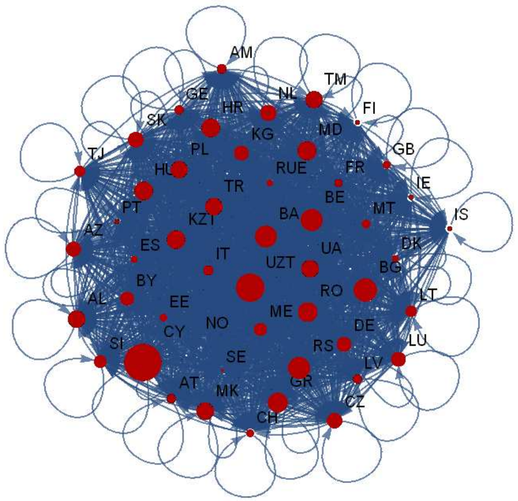

(a) Visualizing polluters' responsibility into 2010 country-to-country blame network for **SOx** deposition



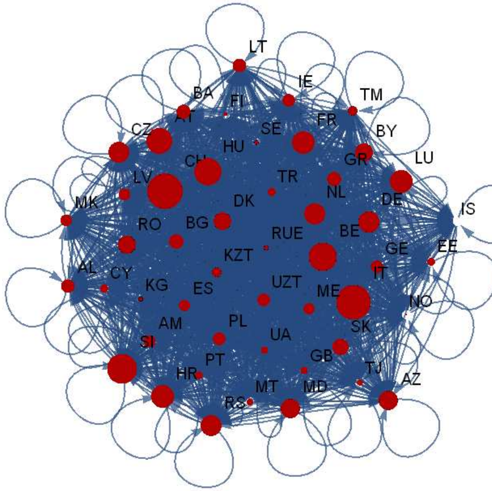

(b) Visualizing polluters' responsibility into 2010 country-to-country blame network for **NOx** deposition



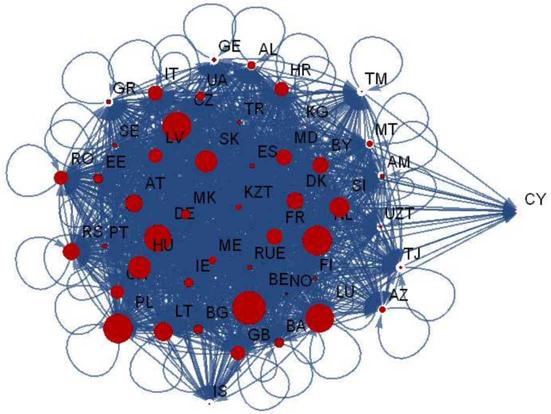

(c) Visualizing polluters' responsibility into 2010 country-to-country blame network for **reduced nitrogen** deposition



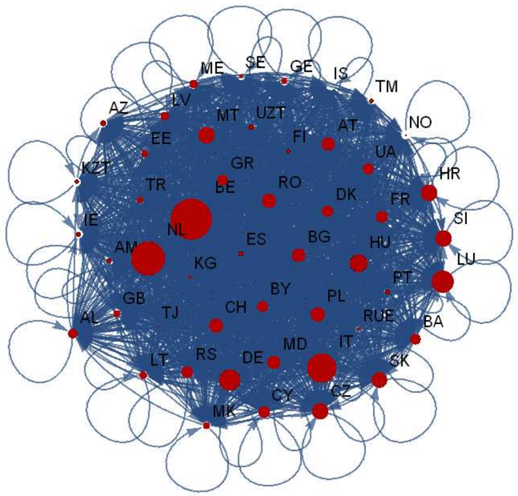

(d) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_SOx**



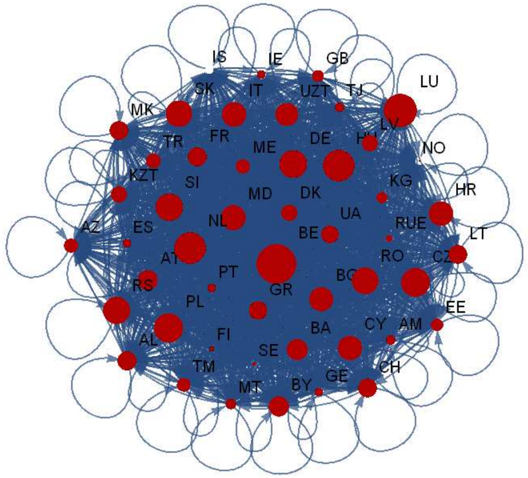

(e) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NOx**




(f) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NH3**

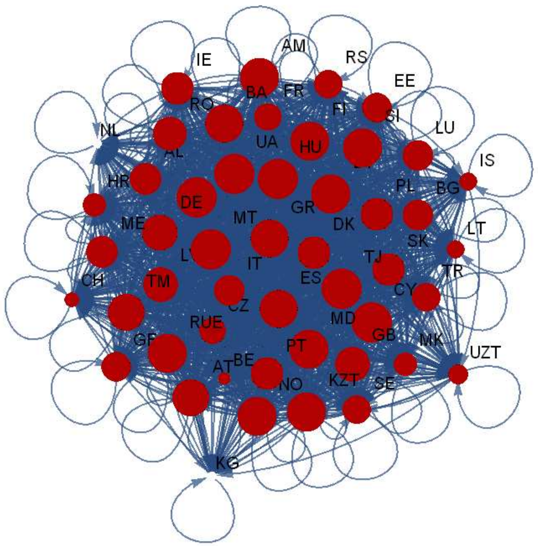



(g) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NMVOC**

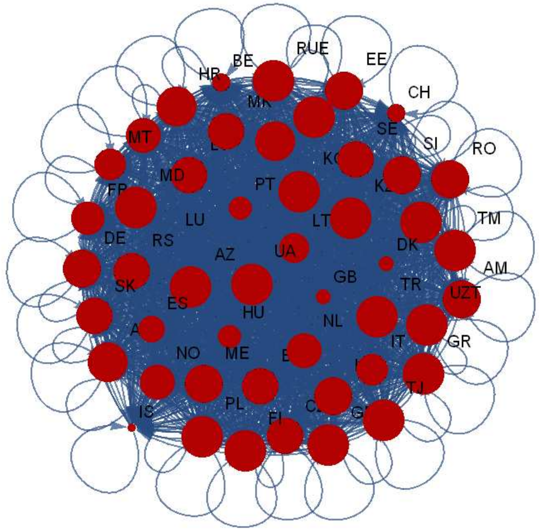



(h) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5**

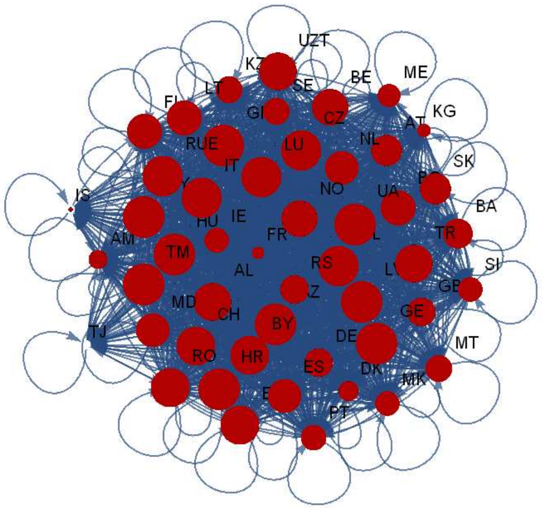
**Figure 3**: Responsibility is quantified by node strength (the sum of edge weights)



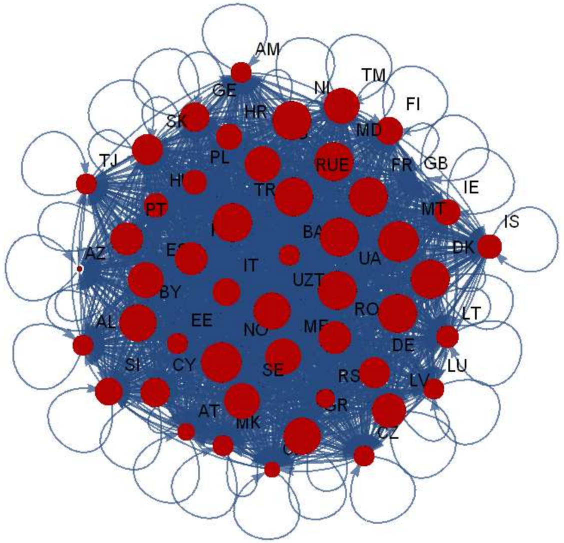
(a) Visualizing polluters' responsibility into 2010 country-to-country blame network for **SOx** deposition



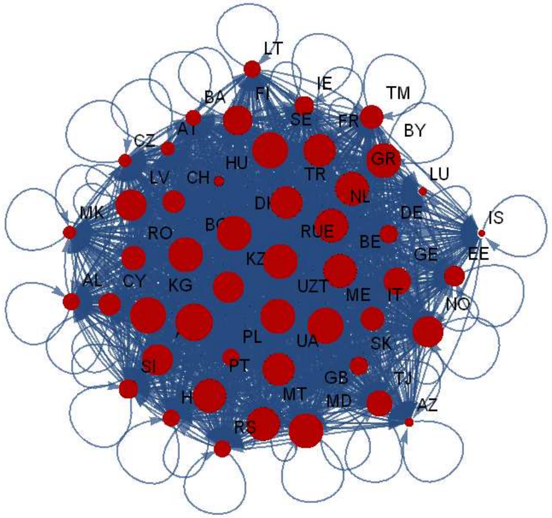
(b) Visualizing polluters' responsibility into 2010 country-to-country blame network for **NOx** deposition



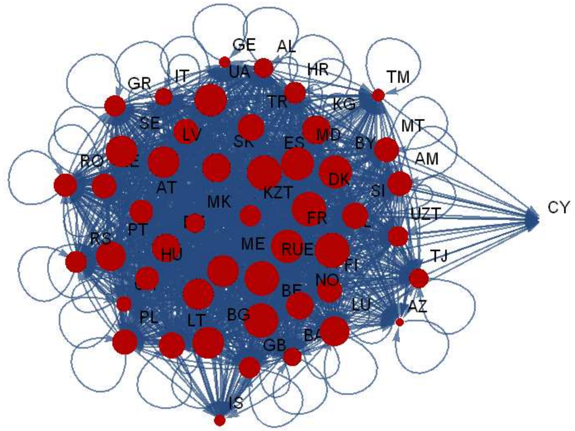
(c) Visualizing polluters' responsibility into 2010 country-to-country blame network for **reduced nitrogen** deposition



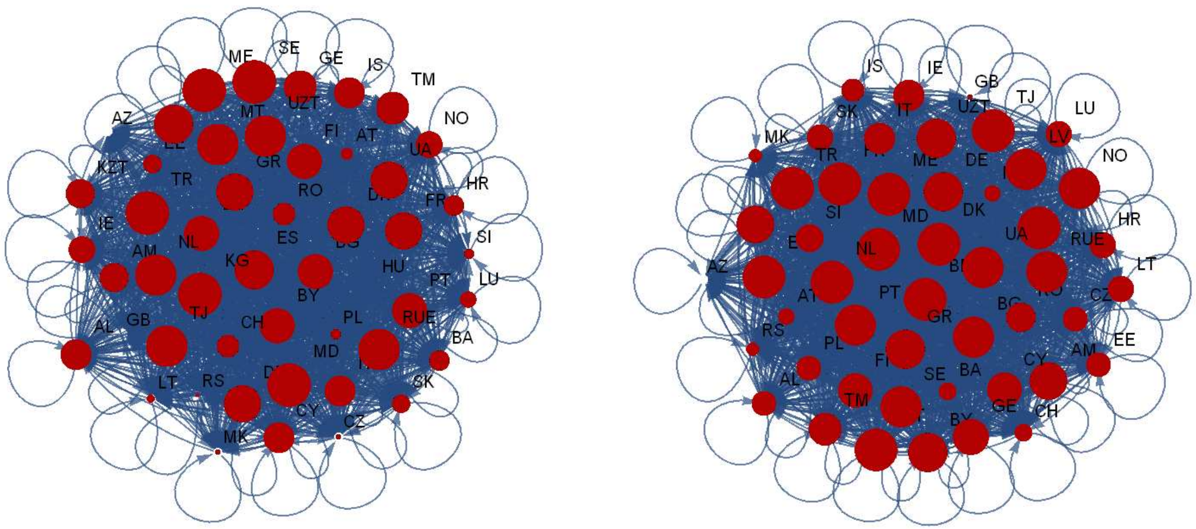

(d) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_SOx**




(e) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NOx**




(f) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NH3**



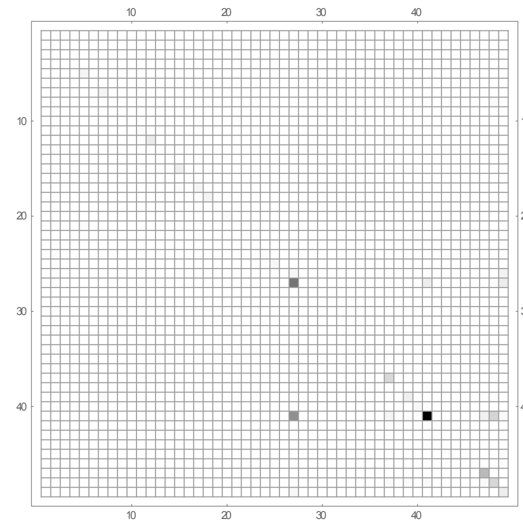

(g) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5_NMVOC**

(h) Visualizing polluters' responsibility into 2010 country-to-country blame network for **PM2.5**

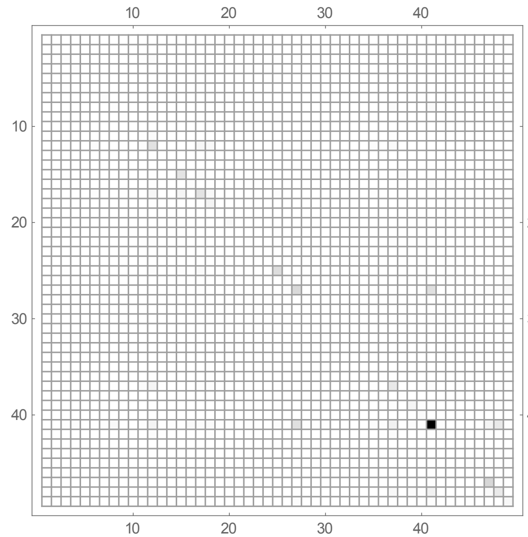
**Figure 4**: Responsibility is quantified by degree centrality (the number of outcoming edges)

Valuable information is gained at a glance from graphics in figure 5. Comparing the pollution patterns of Figure 5a-c, it is evident that the Russian Federation is the major polluter concerning SOx, NOx and reduced nitrogen depositions in the extended EMEP domain, since the darkest matrix cells are constantly observed in this country' row. Unlike SR matrix representations for SOx, NOx and reduced nitrogen, dark shaded cells of SR matrix representations for PM2.5, PM2.5_SOx, PM2.5_NOx, PM2.5_NH3, PM2.5_NMVOC are dispersed all over the matrix range, indicating that pollution peaks are observed all over the EMEP area. SR matrix representations for PM2.5, PM2.5_SOx, PM2.5_NOx and PM2.5_NH3 (Fig. 5d-g) depict intense colors across the main diagonal, an evidence for self-pollution effects. Other indicative findings are that Italy (IT) has the maximum PM2.5_NOx and PM2.5_NMVOC concentration due to self-pollution. The maximum PM2.5_SOx concentration is observed in Turkey (TR) from polluting acts from Cyprus (CY).

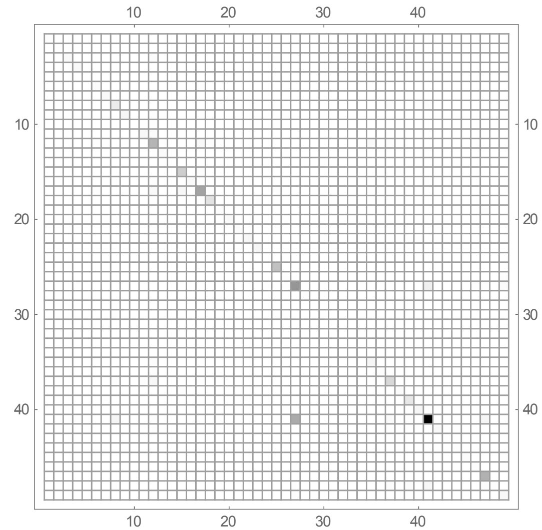
Countries are numbered in the order given in EMEP reports. Namely: 1.AL, 2.AM, 3. AT, 4.AZ, 5.BA, 6.BE, 7.BG, 8.BY, 9.CH, 10.CY, 11.CZ, 12.DE, 13.DK, 14.EE, 15. ES, 16.FI, 17.FR, 18.GB, 19.GE, 20.GR, 21.HR, 22.HU, 23.IE, 24.IS, 25.IT, 26.KG, 27.KZT, 28.LT, 29.LU, 30.LV, 31.MD, 32.ME, 33.MK, 34.MT, 35.NL, 36.NO, 37.PL, 38.PT, 39.RO, 40.RS, 41.RUE, 42.SE, 43.SI, 44.SK, 45.TJ, 46.TM, 47.TR, 48.UA, 49.UZT. Country/region codes are explained in Appendix I.




(a) Table of main **SOx** depositions for 2010

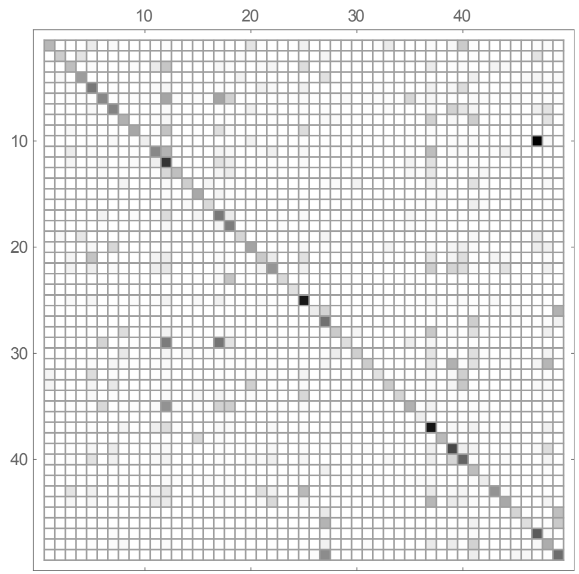



(b) Table of main **NOx** depositions for 2010

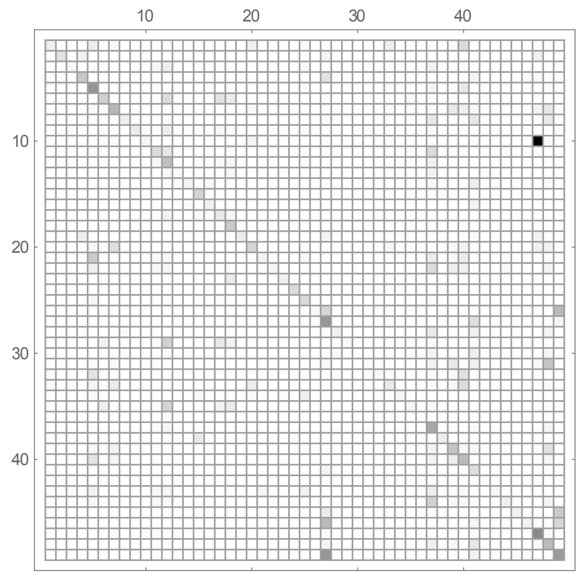



(c) Table of main **Reduced nitrogen** depositions for 2010

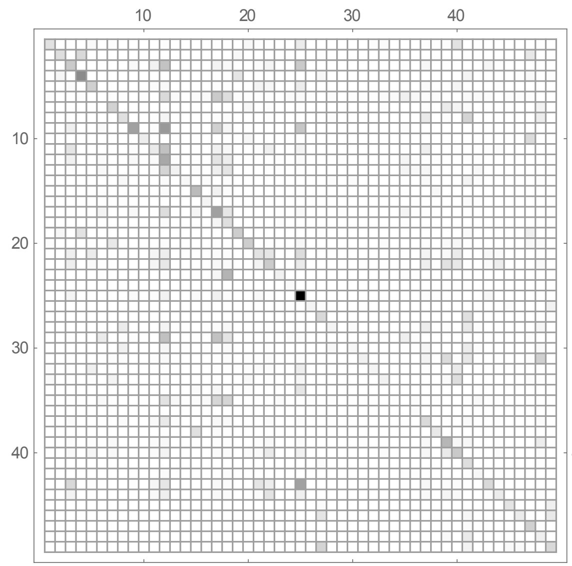
**Figure 5**: The distribution of the highest depositions of pollutants



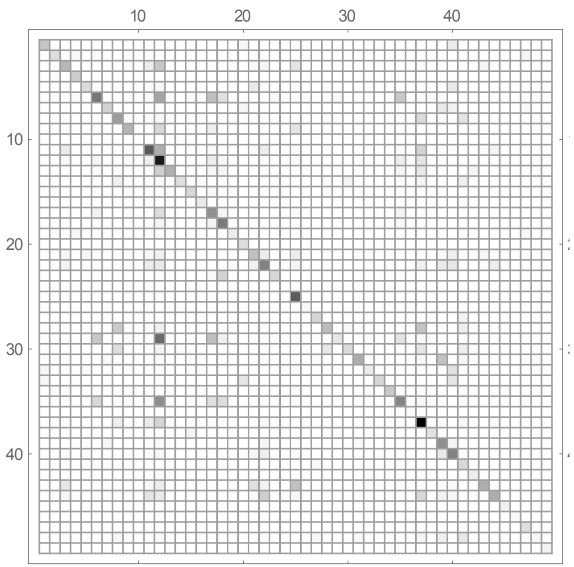

(d) Table of main **PM2.5** concentrations for 2010



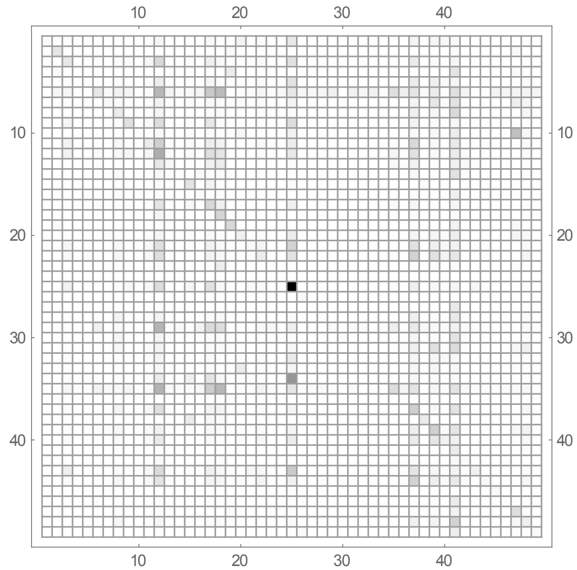

(e) Table of main **PM2.5_SOx** concentrations for 2010




(f) Table of main **PM2.5_NOx** concentrations for 2010




(g) Table of main **PM2.5_NH3** concentrations for 2010




(h) Table of main **PM2.5_NMVOC** concentrations for 2010

**Figure 5**: The distribution of the highest PM concentrations

## 5. Community detecting

Communities in the international country-to-country blame network are represented by clusters of countries, where pollution relationships between countries in the same community are stronger than those between countries in different communities. Community detecting gives a new perspective to qualitative analysis of the pollution interactions.

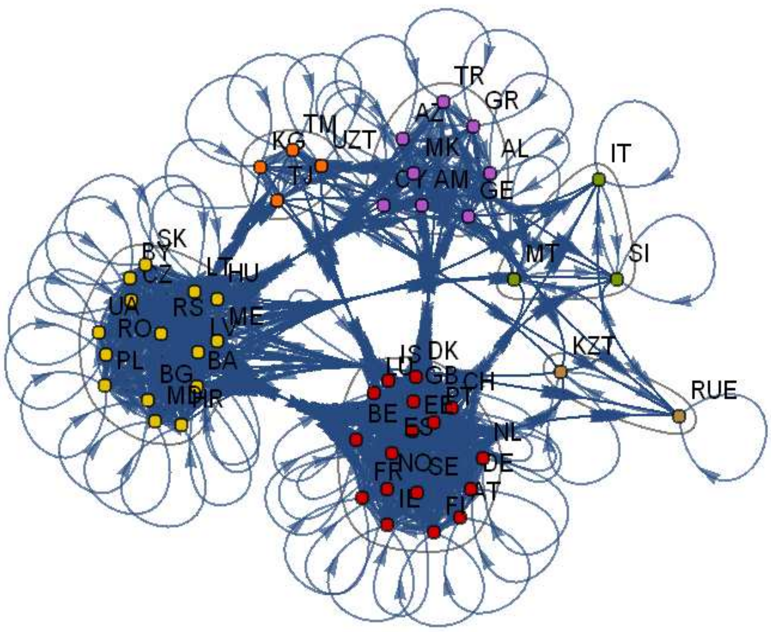



**Figure 6:** The community graph plot for 2010 NOx pollution network. Different colors of the nodes (countries) form different communities.

Mathematica codes that follow, perform modularity-based clustering (by default, `FindGraphCommunities` function uses modularity maximization methods). Modularity is a variable which measures the density of links inside communities compared to links between communities (Newman 2006; Zhong et al. 2017). It is worth noting that neighboring countries form pollution blocks.

SOx

```
FindGraphCommunities[g]

{{AT, BE, CH, CZ, DE, DK, ES, FI, FR, GB, IE, LT, LU, LV, NL, NO, PL, PT, SE},
 {AL, BA, BG, GR, HR, HU, IT, ME, MK, MT, RO, RS, SI, SK}, {AM, AZ, CY, GE, TR}, {KG, KZT, TJ, TM, UZT}, {BY, MD, UA}, {EE, RUE}, {IS}}
```

NOx

```
FindGraphCommunities[g]

{{AT, BE, CH, DE, DK, EE, ES, FI, FR, GB, IE, IS, LU, NL, NO, PT, SE},
 {BA, BG, BY, CZ, HR, HU, LT, LV, MD, ME, PL, RO, RS, SK, UA}, {AL, AM, AZ, CY, GE, GR, MK, TR}, {KG, TJ, TM, UZT}, {IT, MT, SI}, {KZT, RUE}}
```

Reduced Nitrogen

```
FindGraphCommunities[g]

{{AL, BA, BG, GR, HR, HU, MD, ME, MK, RO, RS, SK, UA}, {AT, BE, CH, CZ, DE, DK, LU, NL, NO, SE},
 {BY, EE, FI, LT, LV, PL}, {AM, AZ, CY, GE, TR}, {KG, TJ, TM, UZT}, {ES, FR, PT}, {GB, IE, IS}, {IT, MT, SI}, {KZT, RUE}}
```

PM2.5_SOx

```
In[21]:= FindGraphCommunities[g]

Out[21]= {{BE, CH, DE, DK, FR, GB, IE, LU, NL, NO}, {AM, AZ, GE, KG, KZT, RUE, TJ, TM, UZT},
  {BY, EE, FI, LT, LV, MD, RO, SE, UA}, {AL, BA, BG, GR, HR, ME, MK, RS}, {AT, CZ, HU, PL, SI, SK}, {ES, IT, MT, PT}, {CY, TR}, {IS}}
```

PM2.5_NOx

```
In[21]:= FindGraphCommunities[g]

Out[21]= {{BE, CH, DE, DK, FR, GB, IE, IS, LU, NL, NO, SE}, {BY, EE, FI, KG, KZT, LT, LV, PL, RUE, TJ, TM, UZT},
  {AL, BG, GR, MD, ME, MK, RO, RS, UA}, {AT, BA, CZ, HR, HU, IT, MT, SI, SK}, {AM, AZ, CY, GE, TR}, {ES, PT}}
```

PM2.5_NH3

```
In[21]:= FindGraphCommunities[g]

Out[21]= {{BY, EE, FI, KZT, LT, LV, PL, RUE, UA}, {AL, BG, GR, MD, ME, MK, RO, RS}, {BE, CH, CY, DE, FR, IS, LU, NL},
  {AT, BA, HR, IT, SI}, {AM, AZ, GE, TR}, {KG, TJ, TM, UZT}, {CZ, HU, SK}, {DK, NO, SE}, {ES, PT}, {GB, IE}, {MT}}
```

PM2.5_NMVOC

```
In[21]:= FindGraphCommunities[g]

Out[21]= {{AL, AM, AZ, BG, BY, CY, GE, GR, KZT, LT, LV, MD, MK, RO, RS, RUE, TM, TR, UA},
  {BE, DE, DK, EE, FI, FR, GB, IE, IS, LU, NL, NO, SE}, {AT, CH, HR, IT, ME, MT, SI}, {BA, CZ, HU, PL, SK}, {KG, TJ, UZT}, {ES, PT}}
```

PM2.5

```
In[43]:= FindGraphCommunities[g]

Out[43]= {{BE, CH, DE, DK, FR, GB, IE, LU, NL}, {AL, BA, GR, HR, ME, MK, RS}, {BY, EE, FI, LT, LV, NO, SE},
  {KG, KZT, RUE, TJ, TM, UZT}, {AM, AZ, CY, GE, TR}, {AT, IT, MT, SI}, {BG, MD, RO, UA}, {CZ, HU, PL, SK}, {ES, PT}, {IS}}
```

## 6. Results and Discussion

Network analysis has been applied to science recently (Borgatti and Everett, 2006; Opsahl et al., 2010, Zhang et al. 2017). Our analysis presented visual schemes for the change in depositions of main pollutants - compounds responsible for acidification and eutrophication - and air concentrations of particulate matter, in receptor countries in the EMEP region for year 2010.

Our graph-based calculus resulted in three measures for pollution responsibility. Our computer codes succeeded in estimating all three of them for the countries of extended EMEP region and ranked the countries with respect to their pollution responsibility. Then, using graph model visualization, we made the size of a node-country analogous to its responsibility indicator. Furthermore, we proposed a polluters' clustering technique, as defined in the network context.

Country-to-country blame matrices for air pollution for 2010 consist of 49 rows and columns. Visualization of tabular data makes easy for users to perceive salient aspects of these pollution data quickly. It allows for capturing a big picture of European-wide deposition peaks for SR pollutants.

The visual representations reveal invaluable information about the structure, the flows of EMEP/MSC-W pollution data and the associated responsibility in the EMEP area. A similar analysis could be done for pollution vulnerability and pollution victims. The recognition of these problems and in order to confront with Protocols and Conventions has led to political action in many countries on emission standards and other regulations/ measures in order to protect human health and the environment from adverse effects, as the acidifying effects. Various principles of damage cost responsibility may be facilitated by such a graphical representation in endorsing the country responsible for producing pollution to internalize the externality in terms of the social costs and the damage imposed to the natural environment.

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## Appendix I

| Code | Country/Region | Code | Country/Region |
|---|---|---|---|
| AL | Albania | KG | Kyrgyzstan |
| AM | Armenia | KZ | Kazakhstan (official) |
| AT | Austria | KZT | Kazakhstan (extended) |
| AZ | Azerbaijan | LT | Lithuania |
| BA | Bosnia and Hercegovina | LU | Luxembourg |
| BAS | Baltic Sea | LV | Latvia |
| BE | Belgium | MD | Republic of Moldova |
| BG | Bulgaria | ME | Montenegro |
| BLS | Black Sea | MED | Mediterranean Sea |
| BY | Belarus | MK | The FYR of Macedonia |
| CH | Switzerland | MT | Malta |
| CS | Serbia and Montenegro | NL | Netherlands |
| CY | Cyprus | NO | Norway |
| CZ | Czech Republic | NOS | North Sea |
| DE | Germany | PL | Poland |
| DK | Denmark | PT | Portugal |
| EE | Estonia | RO | Romania |
| ES | Spain | RS | Serbia |
| FI | Finland | RU | Russian Federation (official) |
| FR | France | RUE | Russian Federation (extended) |
| GB | United Kingdom | SE | Sweden |
| GE | Georgia | SI | Slovenia |
| GR | Greece | SK | Slovakia |
| HR | Croatia | TJ | Tajikistan |
| HU | Hungary | TM | Turkmenistan |
| IE | Ireland | TR | Turkey |
| IS | Iceland | UA | Ukraine |
| IT | Italy | UZT | Uzbekistan |

(source: EMEP report 2016)

## Appendix II

The following output in Mathematica sorts from left to right with increasing pollution indicator for year 2010. This kind of ordering results in a ranking from the less to the most polluting country. The output comes along and complements figure 2.

SOx

```
In[36]:= Sort[fulllist, #1[[2]] < #2[[2]] &]

Out[36]= {{MT, 1.82907}, {LU, 14.7378}, {CY, 17.6135}, {ME, 48.4834}, {IE, 58.0736}, {CH, 60.7477}, {DK, 77.9261}, {IS, 78.7407}, {NL, 83.3643}, {SI, 85.1973},
 {AM, 87.9262}, {PT, 97.6385}, {BE, 108.019}, {EE, 110.969}, {AL, 112.502}, {GE, 128.721}, {MK, 131.103}, {MD, 131.516}, {NO, 136.332}, {AZ, 155.594},
 {LV, 155.947}, {LT, 167.915}, {AT, 184.524}, {HR, 216.27}, {SK, 224.43}, {TJ, 235.534}, {SE, 267.724}, {FI, 287.411}, {TM, 294.995}, {CZ, 296.91},
 {GR, 366.761}, {GB, 369.723}, {BA, 389.059}, {HU, 397.299}, {IT, 398.79}, {RS, 438.842}, {KG, 460.006}, {ES, 487.548}, {BG, 519.022}, {BY, 530.943},
 {FR, 568.046}, {UZT, 632.047}, {DE, 825.32}, {RO, 844.39}, {PL, 1117.08}, {TR, 1455.82}, {UA, 1510.67}, {KZT, 3182.04}, {RUE, 6477.62}}
```

NOx

```
In[14]:= Sort[fulllist, #1[[2]] < #2[[2]] &]

Out[14]= {{MT, 1.73918}, {CY, 13.1512}, {LU, 15.1328}, {IS, 20.}, {ME, 33.8558}, {AM, 41.0004}, {IE, 49.7219}, {MK, 68.9603}, {AL, 73.9967},
 {MD, 78.0139}, {GE, 85.0544}, {TJ, 86.9134}, {AZ, 87.1472}, {SI, 89.0391}, {DK, 89.3659}, {BE, 89.5575}, {EE, 92.1786},
 {PT, 96.4749}, {NL, 102.553}, {CH, 112.832}, {LV, 132.564}, {BA, 139.114}, {TM, 139.68}, {LT, 146.711}, {SK, 164.915},
 {HR, 171.809}, {KG, 178.143}, {NO, 189.729}, {GR, 225.92}, {RS, 231.308}, {UZT, 237.892}, {BG, 242.781}, {GB, 251.032},
 {CZ, 255.107}, {AT, 255.474}, {HU, 265.753}, {FI, 289.043}, {SE, 347.108}, {BY, 378.128}, {RO, 462.787}, {ES, 466.393},
 {TR, 640.858}, {IT, 645.264}, {PL, 708.514}, {FR, 790.291}, {DE, 809.354}, {UA, 850.943}, {KZT, 1043.76}, {RUE, 3295.72}}
```

Reduced Nitrogen

```
In[14]:= Sort[fulllist, #1[[2]] < #2[[2]] &]

Out[14]= {{MT, 1.94885}, {CY, 11.5939}, {IS, 14.6442}, {LU, 27.1848}, {ME, 33.647}, {MK, 68.5272}, {MD, 85.6825}, {EE, 91.033}, {AL, 98.4959}, {SI, 99.2443},
 {TJ, 114.12}, {AM, 116.465}, {BA, 134.545}, {PT, 145.798}, {LV, 152.429}, {SK, 162.232}, {DK, 162.565}, {NO, 172.23}, {TM, 175.88}, {LT, 191.197},
 {AZ, 191.664}, {KG, 192.282}, {HR, 193.847}, {GE, 199.327}, {BE, 210.17}, {GR, 213.002}, {IE, 225.065}, {CH, 246.845}, {FI, 251.663}, {BG, 253.963},
 {NL, 278.289}, {UZT, 285.915}, {RS, 287.348}, {AT, 319.763}, {HU, 320.769}, {CZ, 323.071}, {SE, 326.844}, {BY, 515.537}, {GB, 544.632},
 {RO, 560.393}, {UA, 614.002}, {ES, 802.28}, {PL, 894.889}, {IT, 993.519}, {TR, 1113.5}, {DE, 1307.51}, {FR, 1320.24}, {KZT, 1581.6}, {RUE, 3901.78}}
```

PM2.5_SOx

```
In[14]:= Sort[fulllist, #1[[2]] < #2[[2]] &]

Out[14]= {{NO, 39.6018}, {SE, 70.5991}, {IS, 97.0757}, {FI, 104.887}, {IE, 109.758}, {PT, 113.706}, {RUE, 133.753}, {GB, 135.847},
  {DK, 137.023}, {ES, 137.786}, {CH, 144.255}, {EE, 145.987}, {FR, 158.328}, {GE, 168.253}, {MT, 169.065}, {AT, 169.935},
  {LV, 170.287}, {AM, 180.015}, {IT, 186.067}, {TJ, 195.004}, {LT, 198.84}, {SI, 226.413}, {AZ, 233.914}, {ME, 234.873}, {BY, 243.581},
  {LU, 247.243}, {DE, 251.272}, {CZ, 255.915}, {KG, 257.938}, {SK, 266.505}, {NL, 280.058}, {AL, 281.189}, {MK, 282.288},
  {PL, 283.151}, {TM, 291.736}, {TR, 298.438}, {HR, 302.372}, {UA, 303.109}, {HU, 303.672}, {KZT, 309.279}, {MD, 317.363},
  {RO, 320.328}, {GR, 327.897}, {BA, 334.059}, {RS, 336.24}, {BE, 357.388}, {BG, 373.233}, {UZT, 433.672}, {CY, 532.077}}
```

PM2.5_NOx

```
In[14]:= Sort[fulllist, #1[[2]] < #2[[2]] &]

Out[14]= {{IS, 7.22486}, {NO, 14.6065}, {FI, 26.355}, {SE, 29.4608}, {KG, 31.7954}, {RUE, 37.3122}, {TJ, 38.982}, {GB, 39.2647}, {MT, 42.0216}, {UA, 47.7435},
  {EE, 47.8677}, {PT, 49.1985}, {TR, 49.5985}, {CY, 50.8465}, {TM, 58.4934}, {KZT, 60.547}, {MK, 66.2049}, {ME, 69.4014}, {ES, 72.2316},
  {LV, 73.5363}, {PL, 73.998}, {IE, 74.3205}, {AM, 74.402}, {GE, 75.2793}, {AL, 78.6931}, {LT, 78.8984}, {UZT, 78.9243}, {BA, 79.719}, {GR, 86.2924},
  {BG, 87.0649}, {SK, 91.0521}, {AZ, 101.377}, {RO, 102.363}, {DK, 103.058}, {BY, 104.485}, {CZ, 109.284}, {RS, 111.71}, {MD, 113.236}, {DE, 113.328},
  {LU, 115.674}, {NL, 120.079}, {HR, 121.632}, {FR, 126.416}, {AT, 132.203}, {HU, 134.847}, {SI, 153.127}, {BE, 154.422}, {IT, 176.09}, {CH, 178.932}}
```

PM2.5_NH3

```
In[14]:= Sort[fulllist, #1[[2]] < #2[[2]] &]

Out[14]= {{CY, 0.}, {IS, 1.69221}, {TM, 12.9254}, {KG, 19.314}, {NO, 20.8127}, {UZT, 25.436}, {TJ, 26.1529}, {GE, 38.8469}, {TR, 44.3403}, {FI, 44.5489},
  {GR, 49.182}, {AZ, 52.0382}, {PT, 52.8158}, {SE, 52.9457}, {AM, 61.1612}, {RUE, 61.744}, {KZT, 63.5902}, {ES, 65.3907}, {MT, 70.2286}, {ME, 92.3214},
  {AL, 92.4301}, {MK, 104.767}, {BA, 105.524}, {UA, 107.04}, {IE, 108.641}, {EE, 113.344}, {BG, 119.64}, {CH, 135.629}, {GB, 150.236}, {IT, 150.93},
  {RO, 152.506}, {HR, 156.158}, {LV, 162.549}, {RS, 176.816}, {MD, 185.22}, {FR, 186.093}, {BY, 188.023}, {AT, 188.338}, {DK, 196.681}, {LT, 203.074},
  {SI, 213.474}, {HU, 235.352}, {SK, 235.451}, {DE, 283.588}, {CZ, 294.541}, {PL, 297.026}, {LU, 297.814}, {NL, 319.976}, {BE, 355.048}}
```

PM2.5_NMVOC

```
In[14]:= Sort[fulllist, #1[[2]] < #2[[2]] &]

Out[14]= {{IS, 3.75063}, {NO, 8.12911}, {TJ, 9.50538}, {KG, 14.107}, {RUE, 15.4019}, {SE, 18.5684}, {KZT, 19.3457}, {TM, 19.5102},
  {FI, 19.6118}, {AM, 21.9111}, {IE, 22.8694}, {PT, 24.7626}, {AZ, 25.2539}, {ES, 25.5429}, {UZT, 27.214}, {GE, 28.1977},
  {MK, 30.2038}, {GB, 30.4997}, {EE, 31.8315}, {TR, 31.8587}, {LT, 34.8752}, {ME, 41.3543}, {LV, 41.4936}, {AL, 42.6525},
  {BA, 47.2528}, {RS, 49.0033}, {BY, 49.126}, {GR, 49.2465}, {UA, 51.1722}, {DK, 51.8159}, {CY, 52.7258}, {FR, 54.3519},
  {AT, 57.4506}, {PL, 59.4791}, {CH, 60.4462}, {RO, 61.0646}, {BG, 61.1703}, {MD, 62.1237}, {SK, 65.324}, {CZ, 67.2745}, {SI, 67.7213},
  {HR, 68.9454}, {HU, 71.6781}, {MT, 72.6506}, {LU, 88.2361}, {DE, 90.2203}, {IT, 116.64}, {NL, 134.859}, {BE, 155.749}}
```

PM2.5

```
In[36]:= Sort[fulllist, #1[[2]] < #2[[2]] &]

Out[36]= {{IS, 93.5322}, {NO, 99.9185}, {SE, 162.675}, {FI, 202.656}, {RUE, 227.531}, {IE, 266.205}, {ES, 270.856}, {PT, 271.18}, {GE, 272.094}, {AM, 291.282},
  {TJ, 300.607}, {GB, 314.757}, {MT, 323.573}, {KG, 330.471}, {EE, 344.348}, {AZ, 348.54}, {TM, 383.562}, {ME, 403.129}, {TR, 417.817}, {KZT, 438.879},
  {LV, 439.696}, {DK, 447.243}, {MK, 454.542}, {CH, 459.21}, {UA, 468.695}, {LT, 473.864}, {AL, 479.398}, {AT, 484.34}, {GR, 488.662}, {BA, 502.145},
  {FR, 502.985}, {BY, 523.3}, {HR, 582.523}, {UZT, 583.704}, {CY, 595.409}, {IT, 595.816}, {BG, 601.901}, {RS, 605.434}, {SK, 621.365}, {MD, 622.409},
  {RO, 629.165}, {SI, 645.731}, {CZ, 655.036}, {PL, 667.633}, {DE, 673.32}, {HU, 687.686}, {LU, 742.733}, {NL, 748.075}, {BE, 891.626}}
```

The following output in Mathematica gives the set of nodes (countries) with maximum node out-degree. The output comes along and complements figure 4.

SOx

```
In[40]:= GraphHub[g, "Out"]
Out[40]= {AZ, CY, HU, MT, TJ, UA}
```

NOx

```
In[18]:= GraphHub[g, "Out"]
Out[18]= {AT, AZ, BG, FI, GE, GR, KG, KZT, MD, PL, RUE, TJ, TM, TR, UA, UZT}
```

Reduced Nitrogen

```
In[18]:= GraphHub[g, "Out"]
Out[18]= {AZ, CY, GE, GR, HR, HU, LV, TM, UA}
```

PM2.5_SOx

```
In[18]:= GraphHub[g, "Out"]
Out[18]= {MT, NO}
```

PM2.5_NOx

```
GraphHub[g, "Out"]
{ES}
```

PM2.5_NH3

```
GraphHub[g, "Out"]
{ES, NL}
```

PM2.5_NMVOC

```
GraphHub[g, "Out"]
{KG, MD, ME, SE, TR}
```

PM2.5

```
In[40]:= GraphHub[g, "Out"]
Out[40]= {BE, DK, ES, FR, KG, MD, ME, MT, NL, TJ, TR}
```