Mapping actual corrosion rates and exceedances of acceptable corrosion rates – procedure and results

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Abstract

Damages to structural materials, caused by corrosion processes, entail considerable costs. Due to the harmful influence of air pollutants corrosion processes are intensified. Maintenance intervals of buildings and structures are shortened. In order to identify regional differences of intensity of corrosion processes within Germany, maps describing actual corrosion rates have been produced. Mapping procedure and results will be presented and discussed.

There are some material specific spatial patterns of actual corrosion rates within Germany. These regional differences in corrosivity strongly depend on the spatial patterns of the input maps the dose-response-functions require for (climate, air pollutants). Mapping effects when using different kinds of dose-response-functions will be pointed out.

Acceptable corrosion rates mark the dimension of corrosion processes, which is decided to be acceptable in consideration of technical and economic facts. Different weighting factors have been applied in order to calculate and map acceptable corrosion maps. Results of these calculations will be presented.

Further, there will be some short remarks on the assessment of the economic costs of the deterioration of structural materials resulting from air pollutants. The economic assessment has been carried out for the materials galvanised steel, zinc, aluminium, Portland Limestone, Mansfield Sandstone, other natural stones and plaster.

Finally, there will be some notes on how to get more detailed actual corrosion maps in future mapping projects. There are some requirements to the input data, and there are some possibilities to modify the mapping procedure.

1. Dose-Response-Functions

Results of the ICP Materials 8-year material exposure programme have been used to derive dose-response-functions. These dose-response-functions describe the relationship between climate and air pollutants on the one hand and the deterioration of structural material on the other quantitatively. The application of these dose-response-functions has been one of the main aspects of the study (Figure 1).

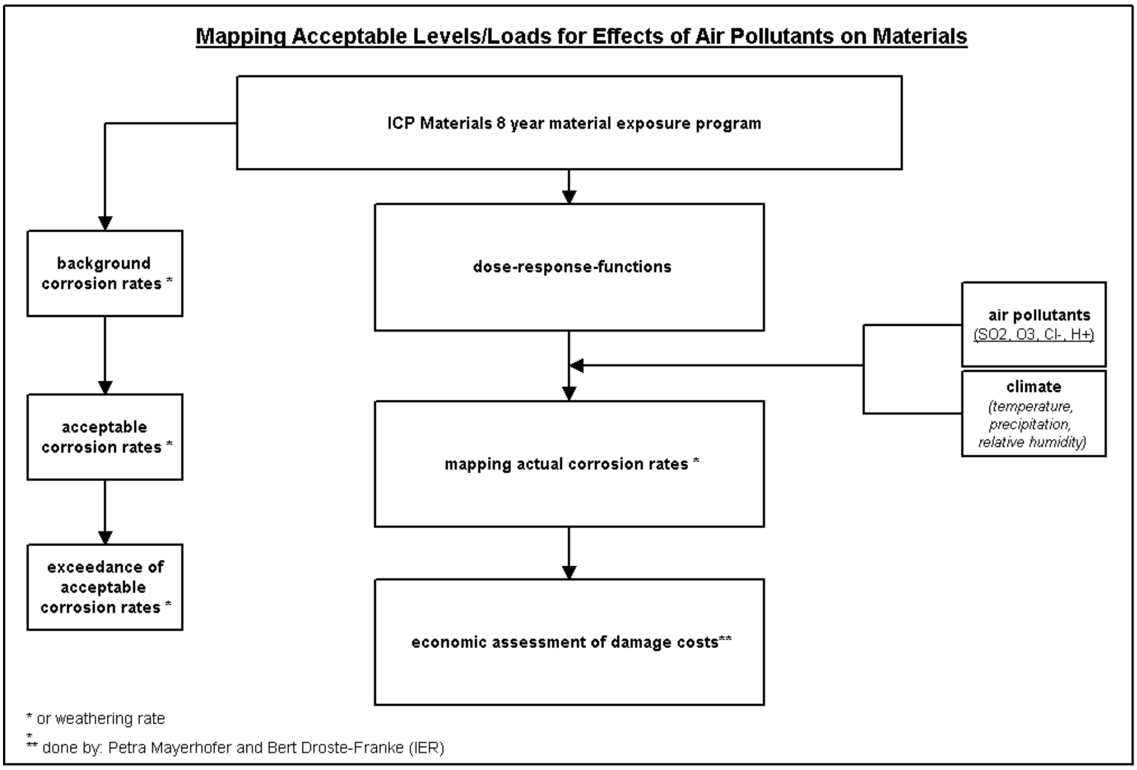

Figure 1: Mapping Acceptable Levels/Loads for Effects of Air pollutants on Materials

Several institutions participated in the analysis of the results of the material exposure programme: The Swedish Corrosion Institute (Stockholm) provided dose-response-functions (ICP-functions) for the materials weathering steel, zinc, aluminium, copper, cast bronze, Portland Limestone, Mansfield Sandstone, coil coated steel with alkyd melamin, steel panels with silicon alkyd, nickel, tin and glass. For the materials weathering steel, copper, cast bronze, zinc, Portland Limestone and Mansfield Sandstone dose-response-functions were elaborated by the Federal Environmental Agency (UBA-functions). In addition, the Bavarian States Conservation Office (BLfD-functions) provided dose-response-functions for copper and cast bronze. Therefore, for several materials two or three different types of dose-response-functions were available to calculate and map actual corrosion rates (Table 1). A comparison has been made between the mapping results of the different types of dose-response-functions.

Table 1: Dose-response-functions for different materials from different institutions

Material	dose-response-functions		
	Swedish Corrosion Institute (SCI)	Federal Environmental Agency (UBA)	Bavarian States Conservation Office (BLfD)
Weathering steel	+	+	
Copper	+	+	+
Bronze	+	+	+
Zinc	+	+	
Portland Limestone	+	+	
Mansfield Sandstone	+	+	
Aluminium	+		
Coil coated steel with alkyd-melamin	+		
Steel panels with silicon-alkyd	+		
Nickel	+		
Tin	+		
Glass	+		

The dose-response-functions require the following input parameters:

- 1. climatic parameters:
  relative humidity in %
  mean annual amount of precipitation in mm
  mean annual temperature in°C

- 2. air pollutant parameters:
  concentration of sulphur dioxide in µm/m³
  concentration of ozone in µm/m³
  concentration of chloride in precipitation wet only) in mg/l
  concentration of protons in precipitation (wet only) in g/l resp. mg/l

Climatic data have been acquired at the German Weather Agency (DWD) as digital maps. Data about the concentration of ozone and sulphur dioxide had to be collected out of the database of the Federal Environmental Agency in Berlin. Data about the concentration of chloride and protons in precipitation have been provided from the States Environmental Agencies, Forest Research Centers, the Federal Environmental Agency and others. In order to calculate grids out of the point data sets of the air pollutant measurement sites Kriging interpolation has been applied. All calculations have been done using ARC/INFO-Geographical Information System.

The dose response-functions from Federal Environmental Agency (UBA) and from Bavarian States Conservation Office (BLfD) calculate actual corrosion rates as yearly mass loss in g/m². The ICP-functions for the materials weathering steel, zinc, aluminium, copper and bronze, too, describe corrosion attack as a yearly mass loss (g/m²). Damage to stone materials is calculated as surface recession in µm. Standards of the American Society of Testing and Materials (ASTM) are used to describe corrosion damage to paint coatings.

Electric contact materials are normally exposed to corrosion in sheltered positions. Therefore the yearly weight increase (µg/cm²) can be used as an indicator of corrosion damages. The actual corrosion rates of glass materials are indicated by the depth of the leached layer in nm.

2. Mapping Actual Corrosion Rates

Mapping actual corrosion rates with different types of dose-response-functions lead to results, which correspond well in magnitude as well as in the spatial patterns of areas of high or low corrosivity. Nevertheless there are some differences concerning the mapping results calculated with different kinds of dose-response-functions. The differences mainly come from using different input parameters. The Federal Environmental Agency´s formula for the material bronze, for instance, considers the concentration of chloride in precipitation. Therefore, the mapping results indicate high actual corrosion rates around the coast line of the North Sea. The ICP-function of bronze does not consider the concentration of chloride in precipitation. Consequently, the mapping results do not show high actual corrosion rates near the coast line of the North Sea. Some differences in mapping results come from differences in the importance, which the formulas put to the several input parameters within the formula (Figure 2 + 3).

For most of the materials SO_2 is the main corrosive agent in the air. Consequently, high actual corrosion rates appear mainly in the regions of highest concentration of SO_2. This is, first of all, the area Halle-Leipzig-Dresden. But also in the Ruhrgebiet and some smaller areas around industrial cities high actual corrosion rates are indicated by the mapping results (Figure 4). In the south of Germany there are large areas with low actual corrosion rates for most of the materials. But there are some more material specific differences in mapping results. The actual corrosion maps of the two paint coatings, for instance, are strongly influenced by the input maps of the climatic parameters.

Dose-response-function (Cast Bronze)

Federal Environmental Agency:

$$^{t}ML_{Bz(un)} \quad = \quad 2{,}83\ t^{0,6} + \{0{,}114\ [SO_2] + 0{,}41\ [Cl^-] + 0{,}015\ [O_3] + 20{,}9\ [RainH^+]\} * t$$

Bavarian States Conservation Office:

$$^{t}ML_{Bz(un)} \quad = \quad INV\ Ln\ (\{Ln\ [t] * 0{,}80316 + [SO2] *1{,}11996E\text{-}02 + [Cl^-] * 8{,}36456E\text{-}02 + [RainH^+] * 3{,}80722 + RH * 1{,}18279E\text{-}02\} + 0{,}57315)$$

To get an annual mass loss:

$$^{j}ML = {}^{4}ML - {}^{3}ML$$

Unified ICP:

$$^{t}ML_{Bz(un)} \quad = \quad 0{,}026\ [SO_2]^{0,44}\ [Rh]\ exp\{0{,}06\ [T\text{-}11]\}\ t^{0,86} + (0{,}029\ [RainH^+] + 0{,}00043\ [RainCl^-])\ t^{0,76} \qquad T\ £\ 11°C \quad (1)$$

$$^{t}ML_{Bz(un)} \quad = \quad 0{,}026\ [SO_2]^{0,44}\ [Rh]\ exp\{-0{,}067\ [T\text{-}11]\}\ t^{0,86} + (0{,}029\ [RainH^+] + 0{,}00043\ [RainCl^-])\ t^{0,76} \qquad T > 11°C \quad (2)$$

^{t}ML - mass loss in g/m² after time in years

Bz - bronze

(un) - unsheltered

t - time in years

$[SO_2]$ - SO_2-concentration (annual mean in µg/m³)

$[O_3]$ - O_3-concentration (annual mean in µg/m³)

$[Cl^-]$ - concentration of chloride in precipitation (mg/l)

Rh - relative air humidity (annual mean)

T - temperature (annual mean in °C)

[RainH+] - product of the concentration of protons in precipitation (mg/l) and the amount of precipitation (mm/year)

[RainCl-] - product of the concentration of chloride in precipitation (mg/l) and the amount of precipitation (mm/year)

Figure 2: Different dose-response-functions for bronze

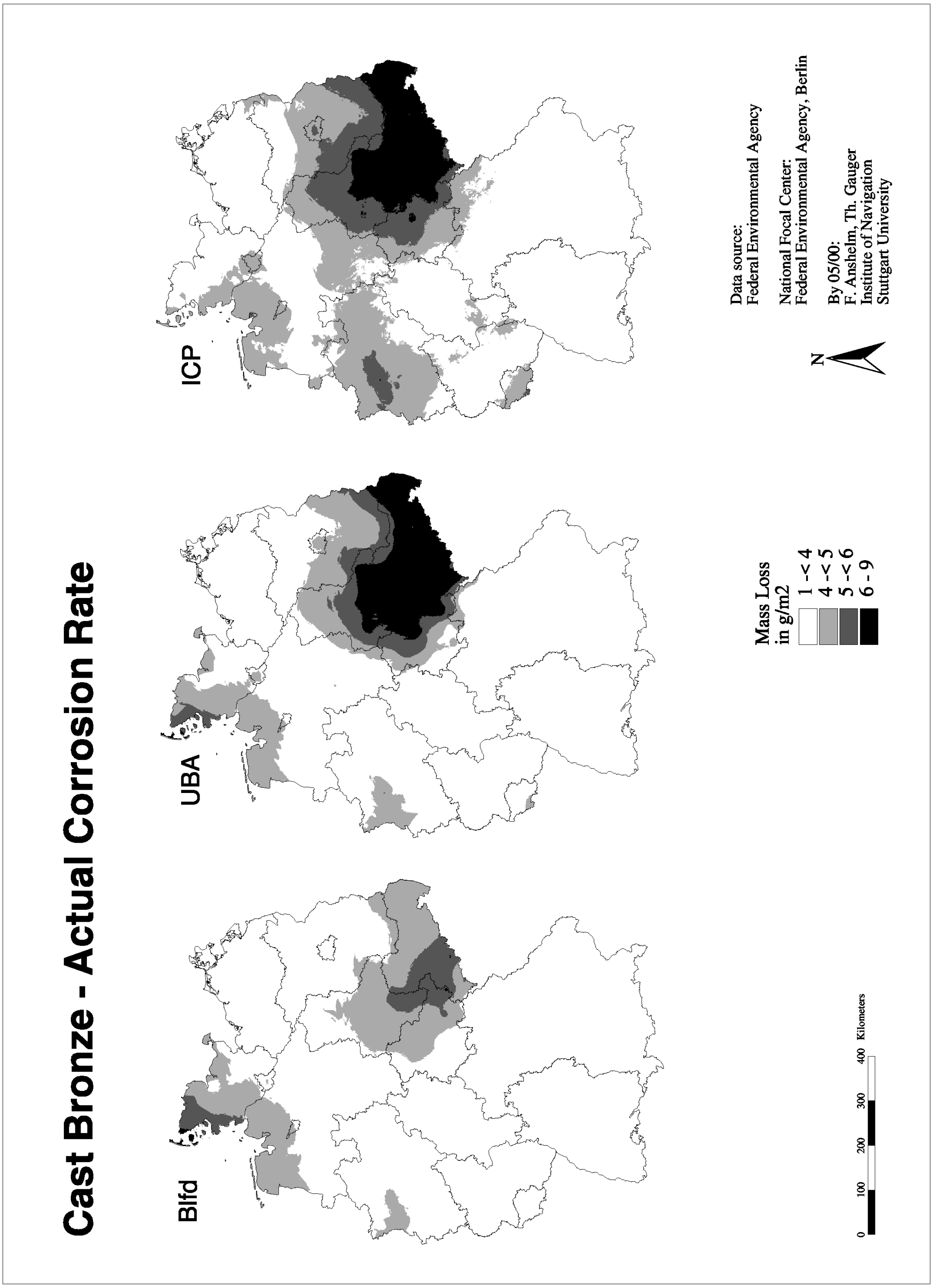

Figure 3: Actual corrosion rate of Cast Bronze

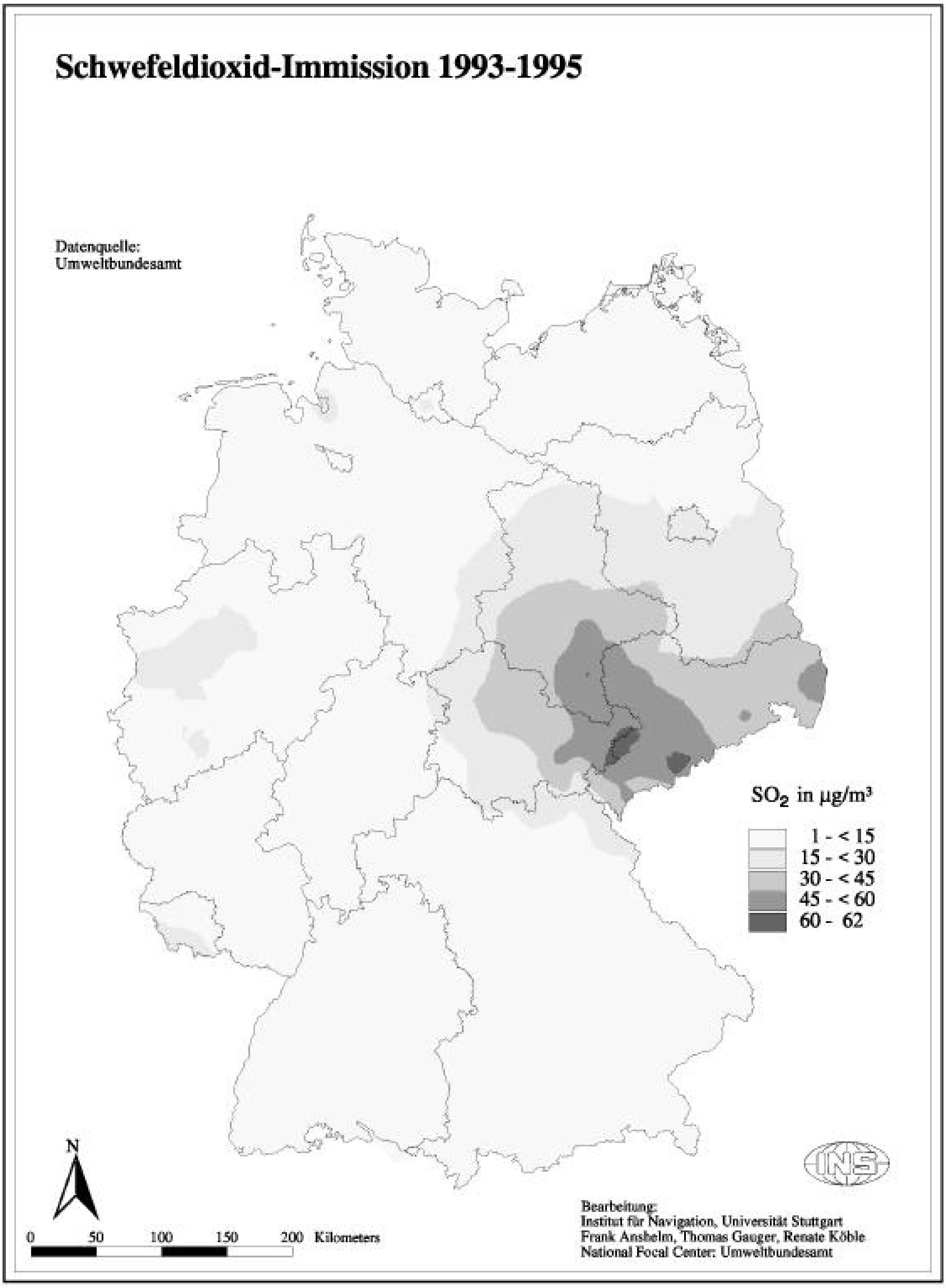

Figure 4: Concentration of SO_2 1993-95

The mapping results of UBA- and BLfD-functions as well as first mapping results of the ICP-functions have been discussed on the UN ECE Workshop on the Quantification of Effects of Air Pollutants on Materials, may 25th -27th 1998 in Berlin. At the end of the meeting it has been decided to use the ICP-functions for future works.

3. Exceedance of Acceptable Corrosion Rates

Another result of the eight year material exposure programme are some values describing the so-called background corrosion rates of the materials. Background corrosion rates mark the natural share of corrosion processes to materials. This natural share has to be considered, if acceptable levels/loads for the effect of air pollutants on materials will be calculated and mapped. Within ICP Materials it was decided to use the lower 10-percentile of all corrosion rates observed during the material exposure programme to describe the background corrosion rates (K_{10}) of the materials.

Table 2: Background corrosion rates

Background corrosion rates (g/m²)	
Copper	3,5
Bronze	2,9
Portland limestone	11
Mansfield sandstone	10
Weathering steel	51
Zinc	4,3

By using the data about the background corrosion rates acceptable corrosion rates have been calculated. Acceptable corrosion rates (K_{acc}) are defined as multiples of the background corrosion rates ($K_{acc} = n \cdot K_{10}$). They mark the dimension of corrosion processes, which is decided to be acceptable in consideration of technical and economic facts. Acceptable corrosion rates have been calculated for the materials weathering steel, zinc, aluminium, copper, cast bronze, Portland Limestone and Mansfield Sandstone. For the materials glass, nickel, tin, coil coated steel with alkyd melamin and steel panels with silicon alkyd no acceptable corrosion rates could be calculated, because essential information about the background corrosion rates were not available. By choosing different values for „n“ ($K_{acc} = n \cdot K_{10}$) three different acceptable corrosion rates have been calculated (n = 1,5 n = 2 n = 3). The three different acceptable corrosion rates apply different standards to the assessment of corrosion damages on the materials.

Low values for „n“ produce strict acceptable corrosion rates and large areas with exceedances of acceptable corrosion rates.

Exceedances of acceptable corrosion rates can be calculated by comparing the actual corrosion rates with the acceptable corrosion rates. These calculations have been done with the unified ICP-dose-response-functions only. The exceedance maps show the regions, where the actual corrosion rates exceed the acceptable corrosion rates and, therefore the damages to buildings and historic and cultural monuments are unacceptably high. Even if n = 3 is used to calculate acceptable corrosion rates, there are exceedances of the acceptable corrosion rates of some materials on to 55 %. If n = 1.5 is used to calculate acceptable corrosion rates, there are high exceedances of the acceptable corrosion rates of all materials in large parts of Germany. For instance, the acceptable corrosion rate of Portland Limestone is exceeded on to about 200 %.

Table 3: Acceptable corrosion rates

Acceptable corrosion rates (g/m²) (n = 1.5)	
Copper	5,25
Bronze	4,35
Portland limestone	16,5
Mansfield sandstone	15
Weathering steel	76,5
Zinc	6,45

4. Economic assessment of material damages

Besides for mapping of acceptable levels the dose-response functions derived in the ICP Materials project can be used for an economic assessment of material damages. The damages are calculated using the so-called *damage function approach*. The dose-response function by itself, however, is not yet a damage function. Only combined with a maintenance criteria the dose-response-function is a *physical damage function*. The physical damage function linked to a material inventory and specific maintenance costs constitutes the *economic damage function*. The advantages of an economic assessment using a damage function approach are that it can be applied to larger areas and that the effort for an update is limited. Due to data availability the assessment is limited to residential buildings in Germany in this study.

The loss of cultural value cannot be assessed at the moment as cultural objects are not inventoried and as there are no uniform specific maintenance costs. It is doubtful that the physical damages could be assessed with the available dose-response functions. Restoration costs can only incompletely be compiled. If put together, it is not possible to clearly attribute the restoration costs to air pollution as the actual restoration expenditures depend mostly on other factors. 'Loss of cultural value' cannot be quantified as there is no general definition of cultural value, that is accepted by conservators and lay persons. If cultural value is a function of the originality and authenticity of an object, any damage is irreversible, as damage *and* restoration of an cultural object are detrimental to its originality and authenticity.

An important part of the work in this study was the derivation of a building and material inventory for 1995, which can easily be updated. Furthermore, the material inventory could be useful for a level II analysis of the acceptable pollution levels for materials. The inventory was derived based on the 'building type' approach. In a first step a building inventory that is differentiated according to building types is calculated based on the building censuses of 1987 and 1995 and updates of the Statistische Bundesamt. In the next step the building inventory is combined with representative surveys on the outdoor surfaces of the specified building types.

With the approach annual damage costs of 430 million DEM are quantified for residential buildings in Germany in the time of 1993 to 1995. These results correspond to annual maintenance costs of about 5 DEM per capita based on the total population in Germany of about 80 million. The galvanised steel surfaces contribute the most to the quantified damage costs. In most regions in Germany annual damages of up to 5000 DEM per km^2 total area are quantified. The highest damages occur in the Ruhrgebiet (up to 46000 DEM/km^2). Other agglomeration areas with relatively high costs (14000–23000 DEM/km^2) are the region around Cologne-Bonn, Stuttgart, the region around Frankfurt, Berlin, Bremen and Kassel.

However, some important damages cannot be quantified as dose-response functions and data are not available. Thus further research on the following points is needed to improve the economic assessment of material damages:

- There are no dose-response functions available for the economically important materials paint and concrete.
- Furthermore, there are no quantitative relationships available for the assessment of soiling of facades etc. due to particulates.
- The material inventory is based on surveys of buildings in Dortmund and Cologne. This is problematic as climatic, economic and cultural factors significantly influence the style and choice of materials used for residential buildings. Surveys of representative buildings in various parts of Germany would improve the reliability of the material inventory.
- There are hardly any empirical data available on what factors influence the decision of house owners to initiate maintenance measures.

The inventory of residential buildings also contains buildings that are seen to be of cultural value. The damages of air pollution to such buildings are in most cases not restricted to maintenance costs. Particularly in the field of economic assessment of cultural value loss due to air pollution there have been only few studies carried out so far.

5. Discussion and future mapping

The dose-response-functions elaborated on the basis of the results of the ICP Materials exposure program are applicable for mapping purposes. On a regional scale areas of high/low actual corrosion rates can be identified. On the local scale corrosion maps are overinterpreted. This is because of the data quality of the required input maps. The density of the measurement networks of the air pollutant input parameters is not high enough to calculate actual corrosion maps, which are valid down to local scale (Figure 5).

The mix of air pollutants has changed during the last decade. The importance of SO_2 has diminished, the relative importance of other air pollutants (O_3, NO_2, particulates) has increased. More detailed information on this topic is presented in the paper of Gauger & Anshelm: „Air Pollutants in Germany: Longterm Trends in Deposition and Air Concentration“ in the workshop proceedings. If new parameters (particulates, NO_2) will be included in the dose-response-functions or if the balance between the input parameters within the existing formulas will change, spatial patterns of the actual corrosion maps can change considerably (Figure 3).

The air concentration of ozone is strongly influenced by the weather conditions in summertime. To equalize these natural yearly variations in ozone air concentration the ozone input maps should be averaged over a longer period of time, for instance over a period of 5 years.

One of the goals of future mapping should be to get more detailed actual corrosion maps (valid down to local scale). It won´t be possible to do this by improving the density of the measurement networks. But there are other ways to modify the mapping procedure, in order to stress differences between urban and rural areas.

The use of different weigthing factors for different landuse classes is one way to calculate maps, which allow to distinguish between rural and urban areas. The damage costs map (Figure 6) already stresses the differences between urban and rural areas, because the stock at risk data, which have been used to calculate the yearly damage costs to residential buildings, are based on small administrative units (Landkreise). In principle, the actual corrosion maps have been weigthed by the stock at risk and other data. Population density, based on data from small administrative units (Landkreise), possibly could be used as a weigthing factor to distinguish between urban and rural areas. Further investigation is needed.

Another way to produce more detailed actual corrosion maps could be to use different input maps for different landuse classes. One assisting map for urban areas, calculated with air pollutant data from urban measurement sites and one assisting map for rural areas calculated with air pollutant data from rural measurement sites. Differences between urban and rural areas should become visible when doing this. The spatial patterns of the output maps would be very similar to the spatial patterns of the landuse map used to distinguish between rural and urban areas. But, if the measurement stations are split into urban and rural sites, the density of the measurement networks, and consequently the interpolation of the measured data becomes worse.

References:

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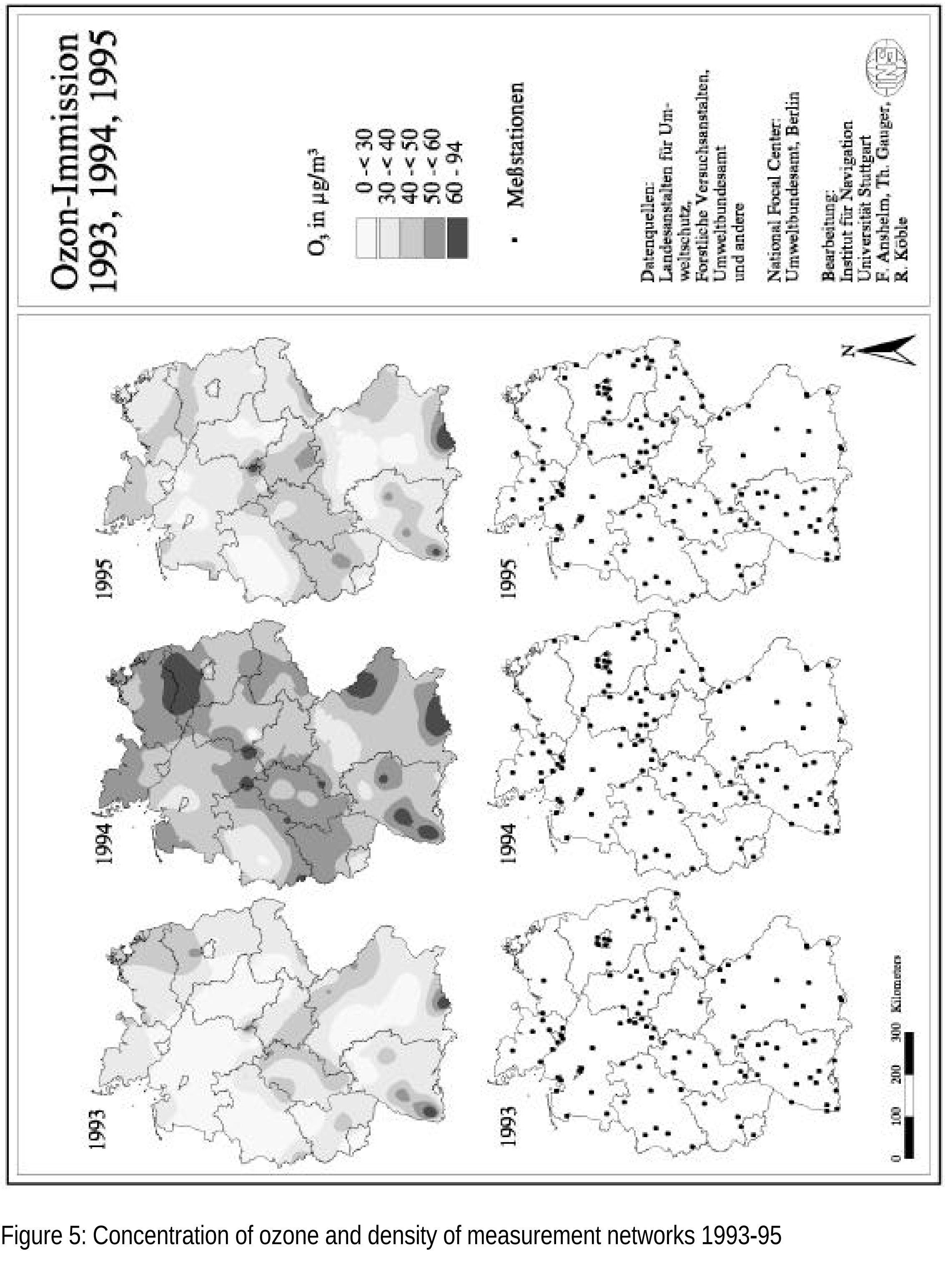

Figure 5: Concentration of ozone and density of measurement networks 1993-95

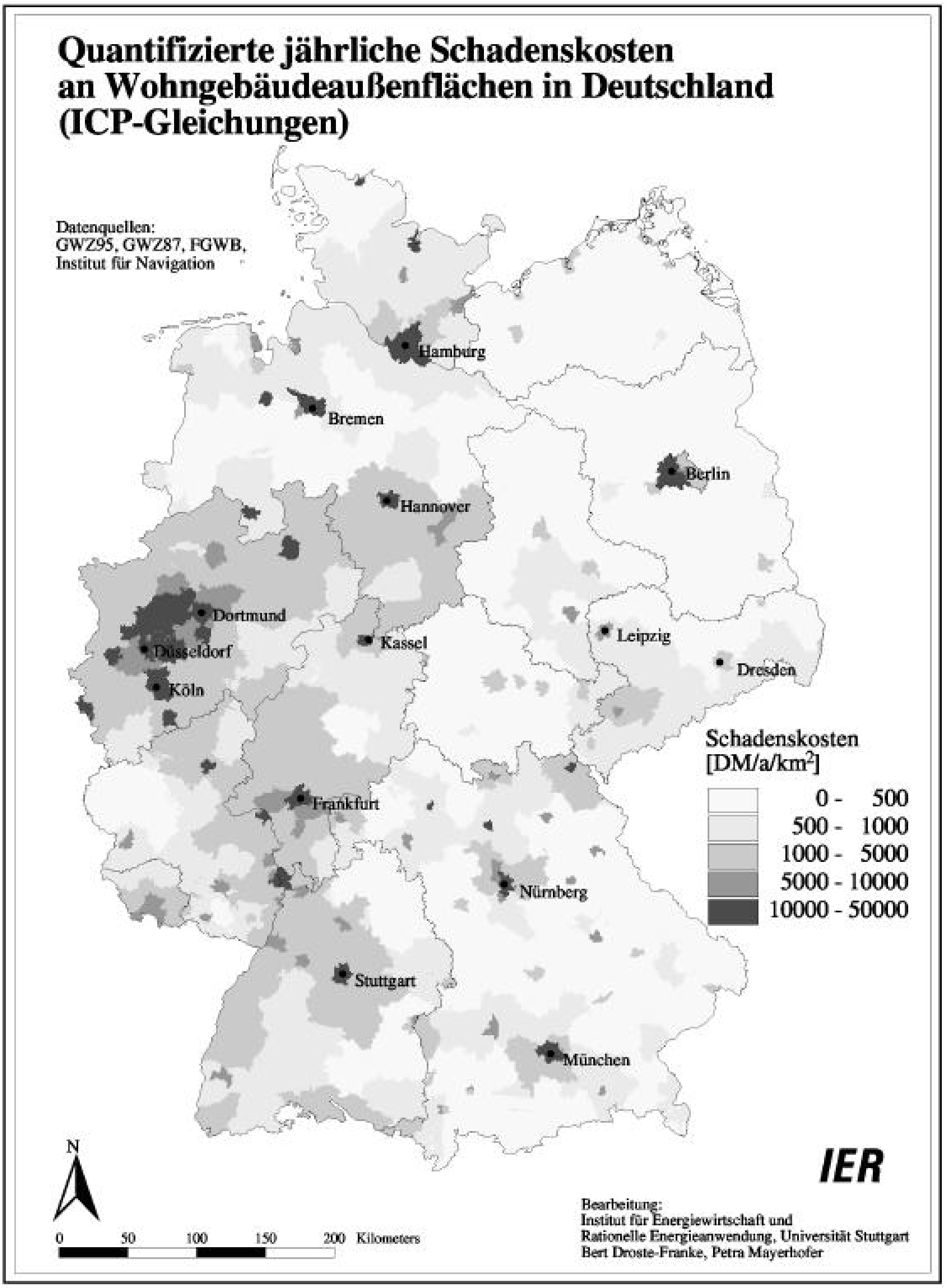

Figure 6: Yearly damage costs to residential buildings in Germany