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Contributors:

Joint Research Centre /Institute for Environment and Sistainability (JRC/IES):
Nicola Lugeri, Carlo Lavalle

International Institute for Applied Systems Analysis (IIASA):
Stefan Hochrainer

Dipartimento di Scienze Agronomiche e Gestione del Territorio Agro-forestale (DISAT):
Marco Bindi, Marco Moriondo

Alterra, Wageningen UR:
Mart-Jan Schelhaas, Nanny Heidema, Geerten Hengeveld, Herbert ter Maat

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Executive Summary

This final report describes the updated results, in terms of maps and methodology, produced by task A2.1 during the second half of life of the ADAM project.

The task 'A2.1 - An assessment of weather-related risks in Europe' had the following main objective:

"*Quantify and map weather-related extreme-event risks to public and private capital assets, human lives, and agriculture/forestry/tourism, and identify high-risk areas ("hot spots") on which to focus more detailed analysis.* "

The key outputs of task A2.1 are digital maps of risks from natural extremes at continental (i.e. European) scale identifying potential economic losses, in present-time conditions. The maps and other processed data are delivered as input to other tasks of Work Packages (WP) under activity A.2 for successive modelling exercises and analysis, in particular to the WP A2.2 (Projections of weather-related extreme event risks to 2025 and 2100). The final report of WP A2.2 includes the results of these processing for future trends for different hazards: monetary losses from floods, risk maps for crops (drought and heat stress) and maps of risk for forest fire and risk from wind storms.

Another important cross-link within ADAM tasks and deliverables is the availability on-line of all of the maps (and more) here presented, via the web page of the so called "Digital Compendium" (deliverable of the WP A.1.5).

This report contains the updated flood and Drought/Heat risk maps, and refers in total to the month 18 deliverable, also published as a JRC internal report (Lugeri et al, 2007) where the methodology was described in detail and the first set of risk maps were presented. This report also contains an analysis of present risks for forest fire and windstorms in forest, which were not included in the previous report.

Additional details can be found in four papers being published in a dedicated issue of the journal "*Mitigation and Adaptation Strategies for Global Change"* (Kundzewicz et al., 2009; Lugeri et al., 2009; Moriondo et al., 2009; Schelhaas et al. 2009).

In terms of results, we find many regions and countries in Eastern Europe to represent flood risk hotspots. At the provincial level, regions in Eastern Europe, central France, and Scandinavia seem to be particularly at risk. These findings are generally in line with the priority areas for action identified in the Green Paper of the European Commission "Adapting to climate change in Europe – options for EU action" (CEC 2007). Aggregation of risks to national level reveals that Eastern European countries seem to be under particular stress. In nearly all new EU member states, annualized flood risk, when measured in share of GDP, exceeds 1 per cent.

As of drought/heat hazard in agriculture, the results indicated that, in present conditions, water stress represents the most limiting factor reducing potential yield, and this is especially true over the Mediterranean basin. The relative importance of heat waves in affecting yield is in fact very low. Summer crops such as sorghum and maize were highly affected by heat waves/water stress whereas the impact of these reducing factor was much lower especially for

barley which is a winter crop partially escaping the risk of higher temperatures and water stress in summer.

Forest fires are especially of concern in the Mediterranean Basin, owing to the severe weather conditions in summer, combined with the widespread use of species that are easily flammable. Incidentally larger fire events occur in other areas of Europe, connected to unusually dry and hot summers. Risk for damage in forest due to windstorms is especially high in the countries bordering the Atlantic Ocean, due to the regular occurrence of high wind speed events. Also Central Europe is prone to high risk, due to the large areas with old spruce stands, which are highly vulnerable and contain much wood.

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1 Introduction

In Europe, adapting to changes in the risk of extreme weather is high on the agenda. Losses from extremes, such as floods, droughts and other climate-related events, have risen sharply in recent decades; a rise that cannot be attributed to increased exposure of economic wealth alone. The IPCC Fourth Assessment Report (2007) concludes that anthropogenic climate change is *likely* to *very likely* to lead to increases in intensity and frequency of weather extremes. This is of concern to European policymakers. The recent EU White Paper 'Adapting to Climate Change: Towards a European Framework for Action'(CEC 2009) has set out an adaptation strategy that, among other things, emphasises the role of disaster risk management. ADAM research has contributed significantly to improving the knowledge base, and identifying knowledge gaps, for managing the changing risks of climate change in Europe.

The overarching methodological approach to this very complex issue relies on the assumption that, although caused by natural events, natural disasters are products of an interaction between nature and the social, economical and political environment which "structures" and configures the lives of individuals, communities and nations (Parker, 2000).

The term *risk* has been defined in several ways in the natural hazard literature. The work here presented follows the generally accepted risk assessment procedure with "risk" understood as a function of hazard, exposure and vulnerability (see Chrichton, (1999) and Kron (2002)) as follows

- *Hazard*: the extreme natural event including its probability of occurrence and intensity;
- *Exposure*: people and assets exposed to hazards;
- *Vulnerability*: the degree of impact/damage incurred by people and assets due to the intensity of an event.

Based on this definition, the risk may be visualised as the area of a triangle (fig. 1.1) with the three above-defined components as sides. Risk can accordingly be decreased by tackling any of the three contributing variables - the hazard, the exposure of the elements and/or their vulnerability. The reduction of any one of the three factors to zero would consequently eliminate the risk (which is impossible).

The main task of every operational approach to risk assessment, both in present conditions and in future scenarios, is the modelling of these components, given the limitations in terms of data availability, resolution and consistency. We have produced maps of flood risk, drought/heat stress to agriculture according to specific models, and of forest fire and windstorm risk according to current inventory data, as presented in the following sections.

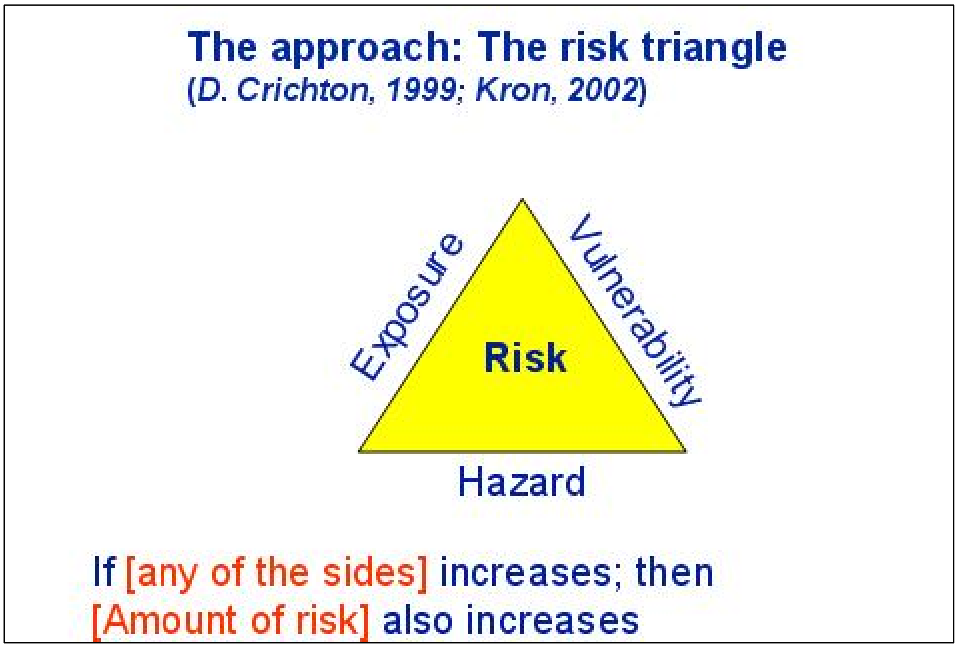


***Figure 1.1**: The risk triangle*

2 Flood risk

2.1 Introduction

Floods have been the most reported natural disaster events in many regions, affecting more than 100 million people, worldwide, in an average year over the last decades. Even if the largest flood disasters occur outside Europe, the EU is not immune to flood hazard. Indeed, large parts of the continent have been hit by major floods in recent decades.

Destructive floods observed in the last decades all over the world have led to record high material damages. Recently, in several individual flood events the material losses exceeded US$ 10 billion, while in each of record-deadly events in less developed countries the number of flood fatalities exceeded a thousand. Most flood fatalities have occurred outside of Europe, in particular in Asia (being endemic in China, India, and Bangladesh). In the summer of 1998, floods in China caused 30 billion US$ material damage and over 3000 fatalities, while in 1996, floods in China caused 26.5 billion US$ material damage and appr. 2700 fatalities. In Bangladesh, during the 1998 flood, about 70% of the country’s area was inundated. (Kundzewicz et al., 2007).

Lugeri et al. (2009) reviewed the recent large-scale flooding in Europe. Even if largest flood disasters occur overseas, Europe is not immune to flood hazard. Indeed, large parts of the continent have been hit by major floods in recent decades. Since 1950, there have been 12 flood events in Europe (flash floods and river floods) with number of fatalities exceeding 100 in each (Barredo, 2007), therein five events in Italy (1951, 1954, 1966, 1968, 1998) and two each in Romania (1970, 1991) and Spain (1962, 1973). The killer-flood in Spain in 1962 was the only event in the last 50 years in Europe leading to more than 1000 fatalities.

The severe floods in Europe in the 2000s were mostly caused by heavy rain. The most destructive flood events occurred in August 2002, when in five countries (Czech Republic, Germany, Austria, Hungary, and Romania) the number of flood fatalities reached 55 and the material damage soared to 20 billion US$. Since in September 2002 another major flood (with 23 fatalities and 1.2 billion US$ in material damage) occurred in France, the year 2002 is recognized as the record-holding year in Europe in the category of highest material damage caused by floods. Serious floods in the UK in October-November 2000 caused 13 fatalities and over 8.9 billion US$ in damage. Multiple waves of heavy rains, leading to destructive floods with dozens of fatalities and billion-high damage occurred in Romania in 2005, while in August 2005, several European countries experienced another major flooding, again with billion-high material damage. In June and July 2007, in result of several waves of intense precipitation, total material flood damage of 8 billion US$ and insured damage of 6 billion US$ were noted in multiple shires (counties) of the UK.

Even if most dramatic floods in Europe in the last decades have been rain-caused, rapid snowmelt has also led to flood disasters, even if snow cover has been, on average, decreasing in the warming climate. The winter of 2005/2006 was cold and snowy over much of European continent, so that a thick snow cover built up and its rapid melt (in some areas, superimposed on heavy rain) resulted in major floodings in such countries as Romania, Hungary, Greece, Turkey, Bulgaria, Serbia-Montenegro, Czech Republic, Slovakia, Germany, Austria, with fatalities and high material damage.

2.2 Method

Our work is based on the standard risk analytical approach of the "risk triangle" at European scale, based on input data describing the three components of risk (exposure, vulnerability, hazard) in a way consistent to the scale of the study, the best possible trade-off between the available data and an acceptable level of uncertainty.

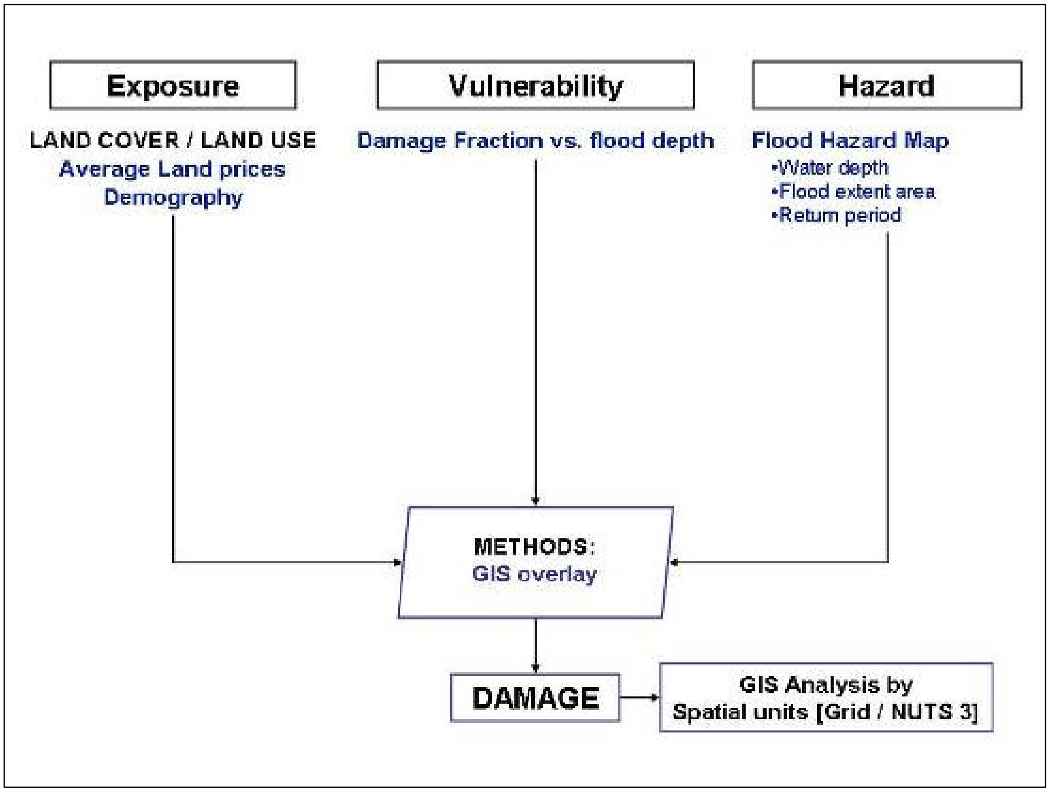


***Figure 2.1**: Operational scheme for the evaluation of the potential flood damage*

Exposure: the main element for the computation of exposure is the CORINE Land Cover (CLC) map of the European natural and artificial landscape. The combination of hazard and land cover maps allows the estimation of the exposure to floods of physical assets which are in turn grouped according to the classes of the land cover map. CLC has a nominal scale of 1:100000, with a minimum mapping unit of 25 hectares and has been operationally used in the raster version with 250m * 250m grid cell size (EEA, 2000).

Vulnerability: the damage caused by floods may depend on each one of the main characteristics of the flood itself. However, the only operational possibility to quantify these effects, in terms of data availability over the whole Europe, was to consider the flood depth alone. Therefore, the vulnerability of the assets under threat has been estimated by means of depth-damage functions for each land use class of CLC for all EU 27 countries. Such functions are operationally expressed as a multiplying factor **V(h)** (with h the flood depth), where $0 \leq \mathbf{V(h)} \leq 1$.

Hazard: flood hazard maps are generated from catchment characteristics. The main data component in this respect is the Digital Terrain Model (DTM), which allows an evaluation of the water depth in each location after a given flood extent.

The flood hazard map used in this analysis is obtained from a 1 km * 1km grid DTM and the dataset of European flow network (Vogt, 2007), with the same grid size, developed by the Natural Hazard Action at the JRC (De Roo et al., 2007). It provides quantitative information on both the expected extent of flooded area and on the water depth.

The map is solely based on topographic features: an algorithm has been developed to compute the height difference between a specific grid-cell and its closest neighbouring grid-cell containing a river, while respecting the catchment tree-structure (Barredo 2005). Details of the computations and examples of validation of the flood hazard map are given in (De Roo et al. 2007). We can therefore say that this hazard map provides a "static" information, differently from hydrological model-based maps which provide probabilistic information arranged in terms of return periods (T_R) or probability of exceedence (P_R). The latter two quantities are reciprocal of each other and respectively describe the time span which (statistically) separates two flood events exceeding a given magnitude, or the yearly probability of occurrence of an event exceeding a given magnitude.

Given the scale of the analysis (macro scale, according to FLOODsite, 2006) and the corresponding level of detaill, as well as the data availability and the relatively small computation requirements, it was performed a probabilistic read-out of the topography-based hazard map (Lugeri et al., 2009) through expert judgment and calibration from the LISFLOOD hydrologic model (de Roo, 1998), which was available for some catchments of Europe.

The computation of monetary flood risk relies on GIS processing of hazard maps and territorial databases (the CLC and the stage-damage functions) combining the probability and severity of flooding with spatially explicit information on exposure and vulnerability. Model outcomes are grid based maps (pixel resolution 250m * 250m) of monetary damage computed for five return periods (50, 100, 250, 500 and 1000 years).

The basic maps can be further elaborated to produce an estimate of the expected loss value over larger grids (like, for example, those used for macroeconomic or climate change models) and administrative level of various detail (from national to regional-provincial), as well as integrated over time to produce the so-called Annual Average Damage, which is one of the most widely used quantities in flood damage assessment (FLOODsite, 2006). Our method provides minimum and maximum values for each return period, according to the range of uncertainty (see Lugeri et al., 2007).

The aggregation of the results over territorial units have been performed in two ways:

1. Simple sum: If no spatio-temporal correlation of flood events is introduced in the spatial analysis, the only aggregation method is the simple sum. That is, if we focus on administrative level like, e.g., NUTS2 (CEC, 2003), the damage is the sum of each "elementary spatial damage unit" (the pixel encoded with its depth-dependent damage), over each administrative unit. The damage is therefore the accumulation of the contributions coming from the exposed portions of land.

2. Hybrid Convolution: this is a new method, expressly designed within this project. It is based on the idea that, depending on the magnitude of the hazard, losses in different elementary spatial units (clusters) and their aggregation in a certain area are assumed to be co-monotonic, i.e. up to a given magnitude of the hazard and a given size of the group of clusters, the losses are assumed to be independent, and afterwards they are assumed to be correlated. As the combination of two independent distributions is called "convolution", and the combination of two dependent distributions is simply the sum, we have called this technique "Hybrid Convolution".

The clustering scheme to be used as basic spatial aggregation frame was defined according to the river catchment structure. In order to achieve a national (NUTS0) or regional (NUTS2) breakdown of this catchment-based aggregation method, these calculations were performed nation- or region-wise, by selecting the elementary clusters belonging to each administrative unit at the chosen NUTS level.

2.3 Results and maps

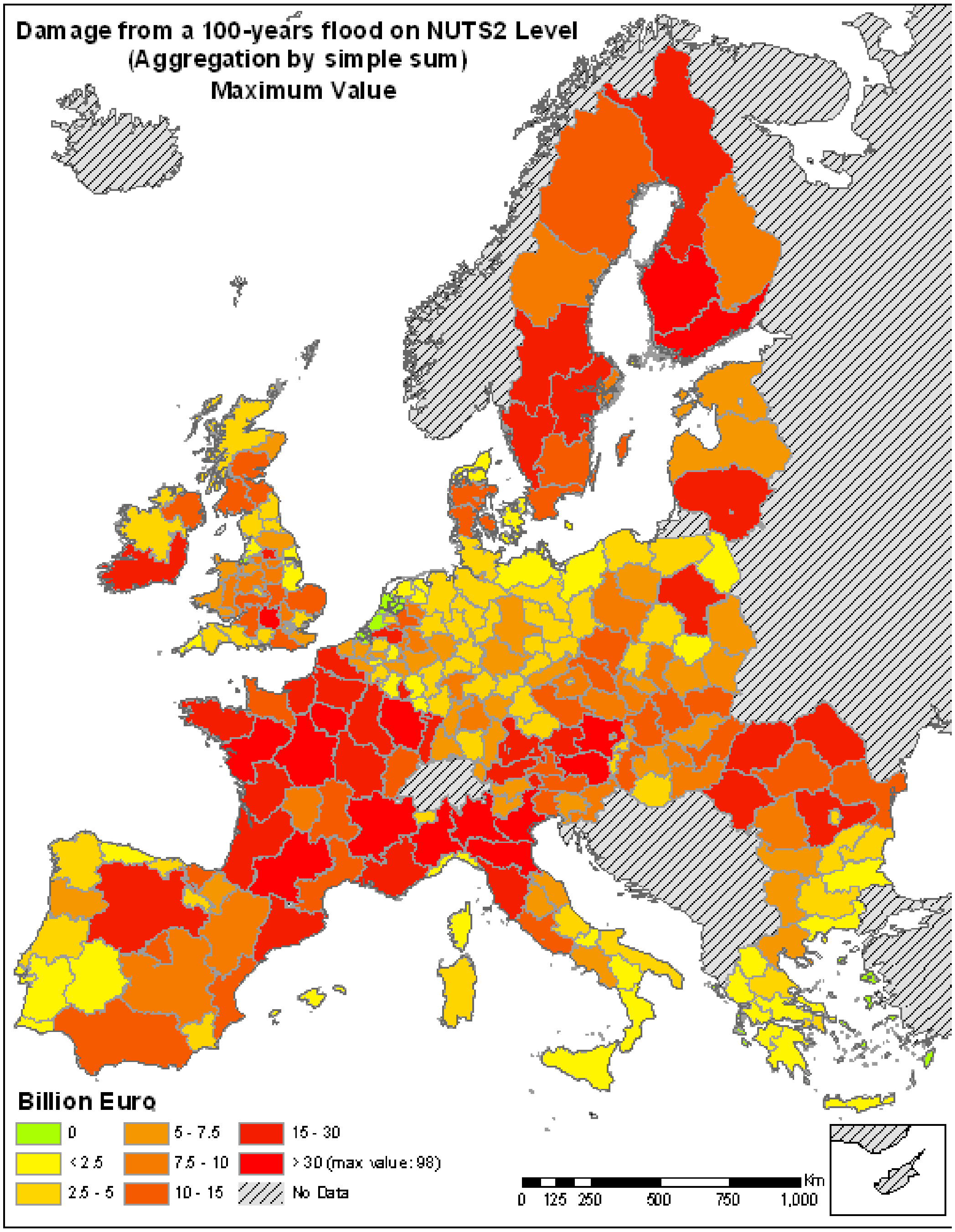
In this section, the maps of the estimated regional (NUTS2) Annual Average Damage from river floods in Europe, as well as the losses expected from a 100-years flood, are shown, for both aggregation schemes. In the case of the AAD maps, the monetary losses are also expressed as a ratio to the respective regional GDP.

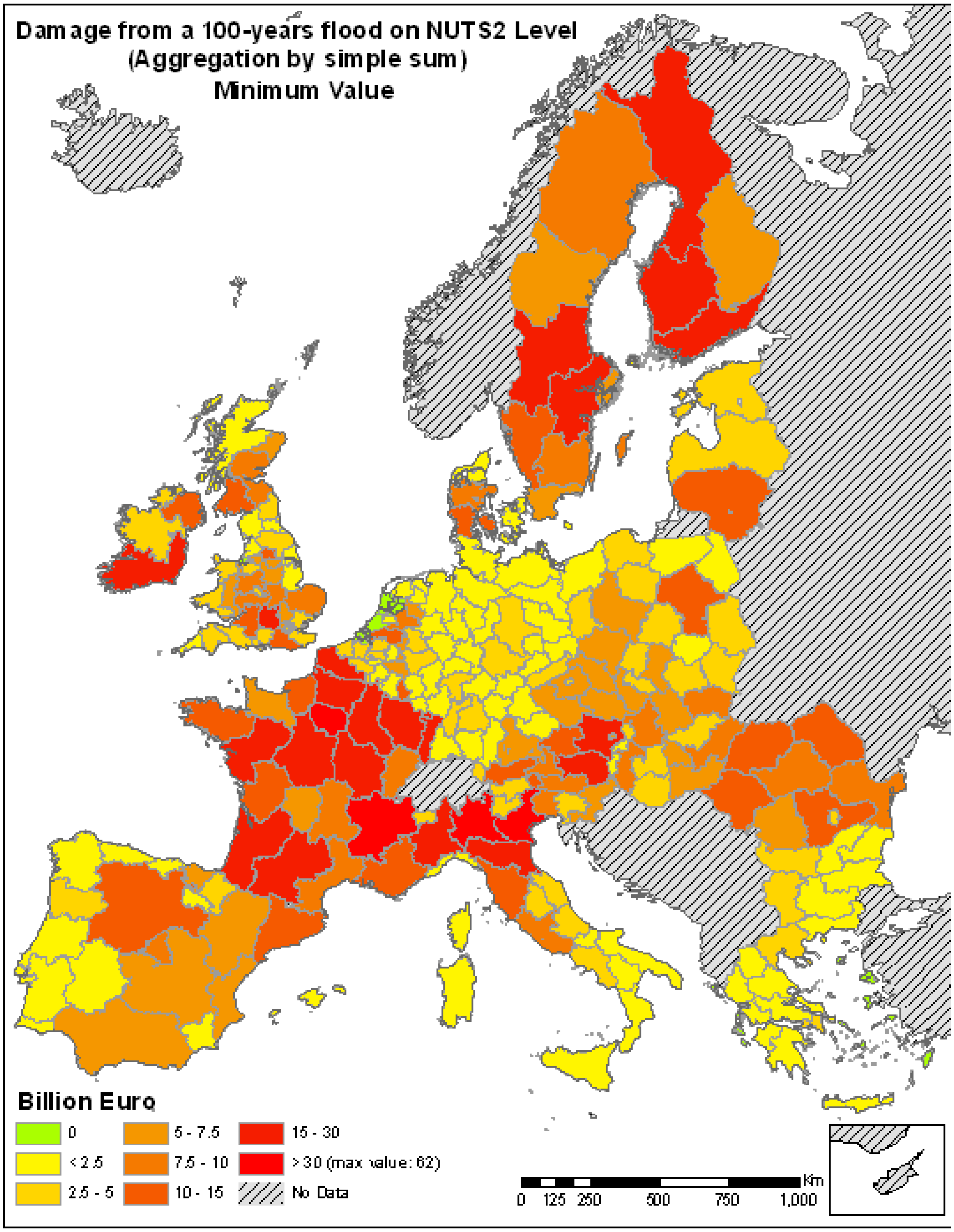
The results, expressed in terms of the Annual Average Damage, highlight regions where the threat to the economy coming from river flood hazard seems to be of major concern. Although the two aggregation methods used yield slightly different results, eastern Europe as well as Scandinavia, Austria and the U.K., along with some regions in France and Italy, show up as being under substantial threat. Aggregation of risks to national level reveals that Eastern European countries seem to be under particular stress. In nearly all new EU member states, annualized flood risk, when measured in share of GDP, exceeds 1 per cent.

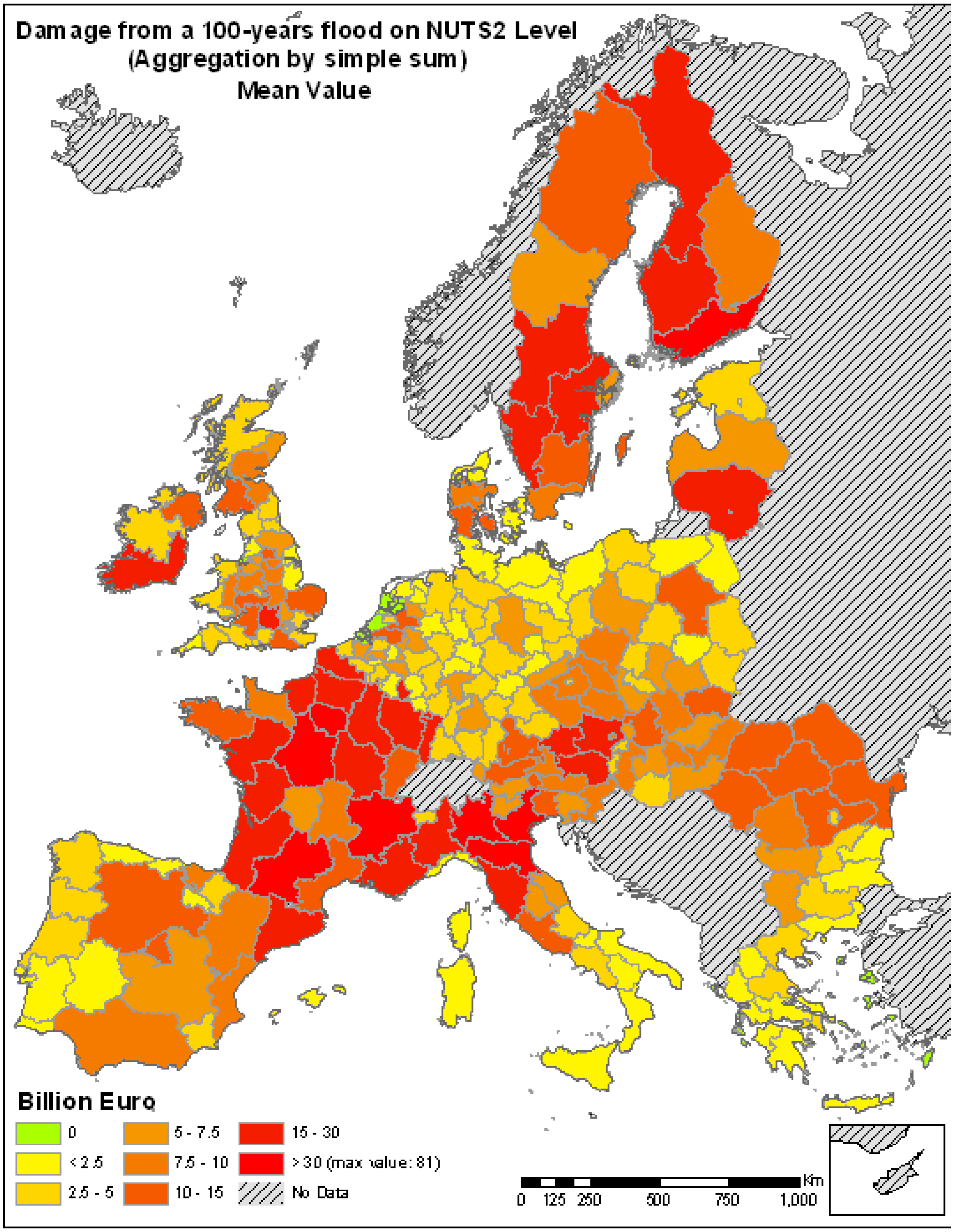
The easiest aggregation method, the simple summation over the administrative units, definitely overestimates the losses. Nevertheless, it is our feeling that – for the time being – it is more reliable than the hybrid convolution method. This is especially the case when a conservative ("protectionist") view is preferable, and to better draw the attention of policy makers to possible risk "hotspots".

In addition to that, due to the scale of the study and the corresponding level of detail of the base data, the overestimation which is intrinsic to the method and arising from the aggregation procedure, to some extent compensates the lack of contribution to the losses from smaller rivers which are not included in the river network.

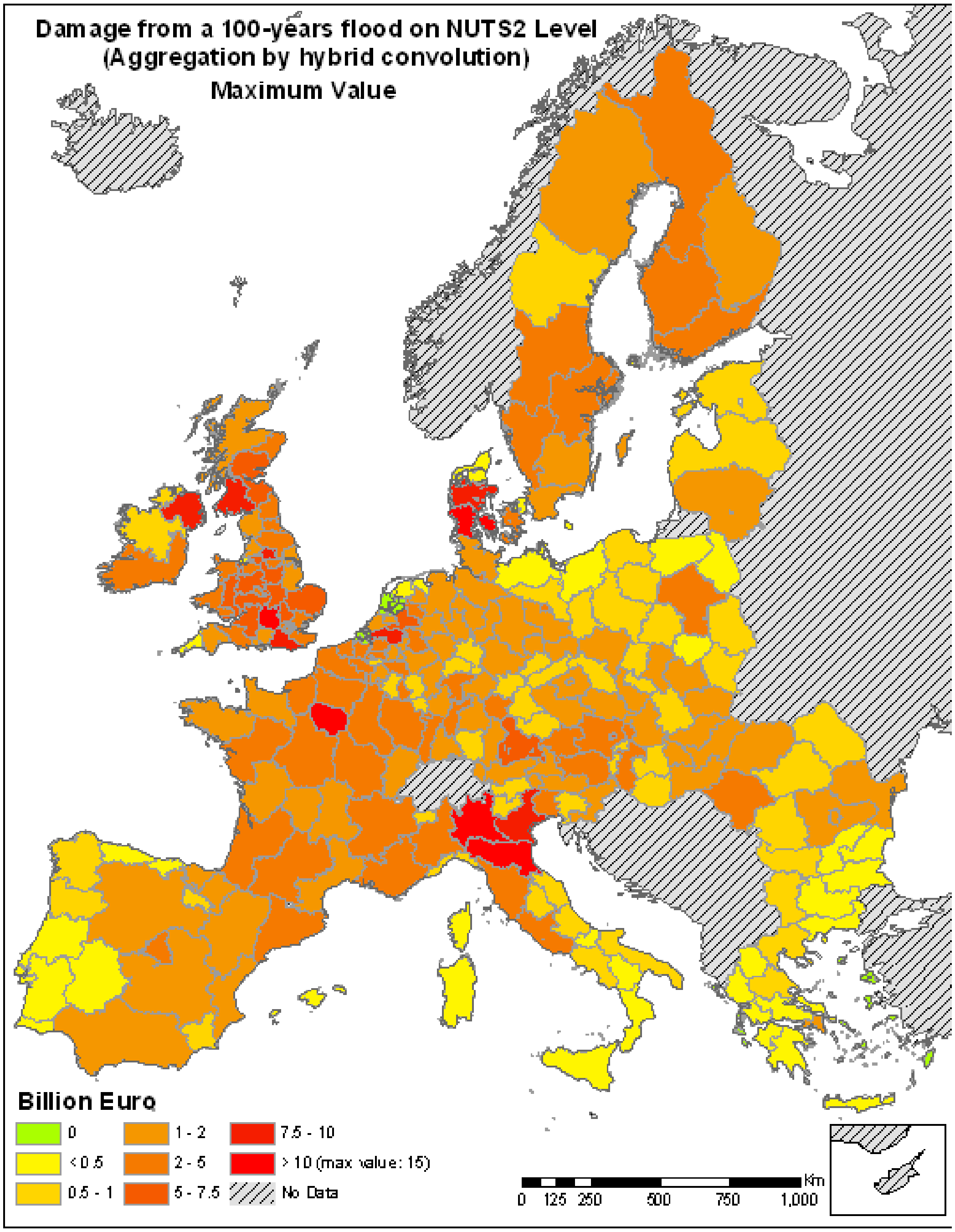
2.3.1 Maps of the expected damages from a 100-years flood: aggregation by simple summation over NUTS2 regions

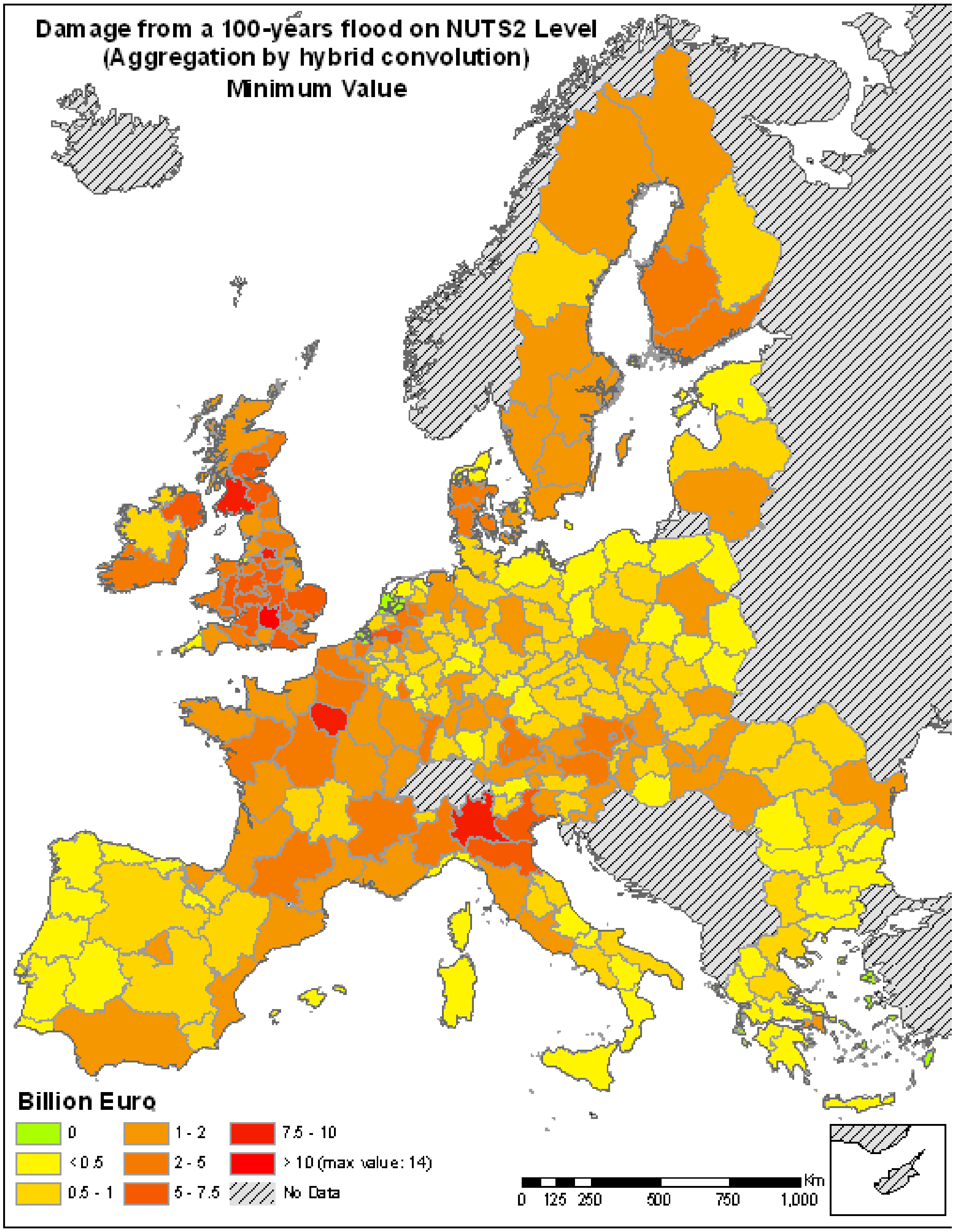


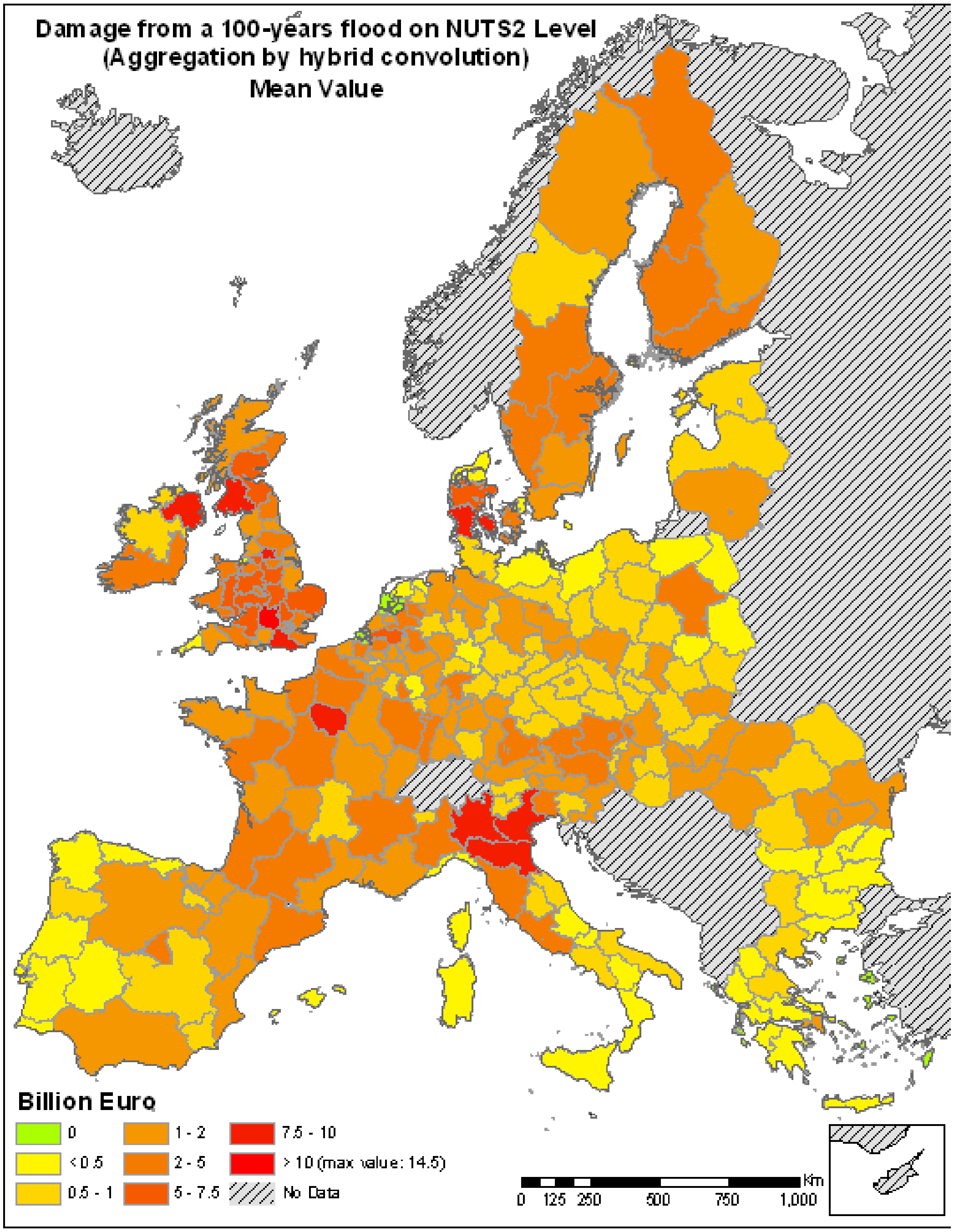

Damage from a 100-years flood on NUTS2 Level
(Aggregation by simple sum)
Minimum Value
Billion Euro
0
< 2.5
2.5 - 5
5 - 7.5
7.5 - 10
10 - 15
15 - 30
> 30 (max value: 62)
No Data
0 125 250 500 750 1,000
Km


Damage from a 100-years flood on NUTS2 Level
(Aggregation by simple sum)
Mean Value
Billion Euro
0
< 2.5
2.5 - 5
5 - 7.5
7.5 - 10
10 - 15
15 - 30
> 30 (max value: 81)
No Data
Km
0 125 250 500 750 1,000

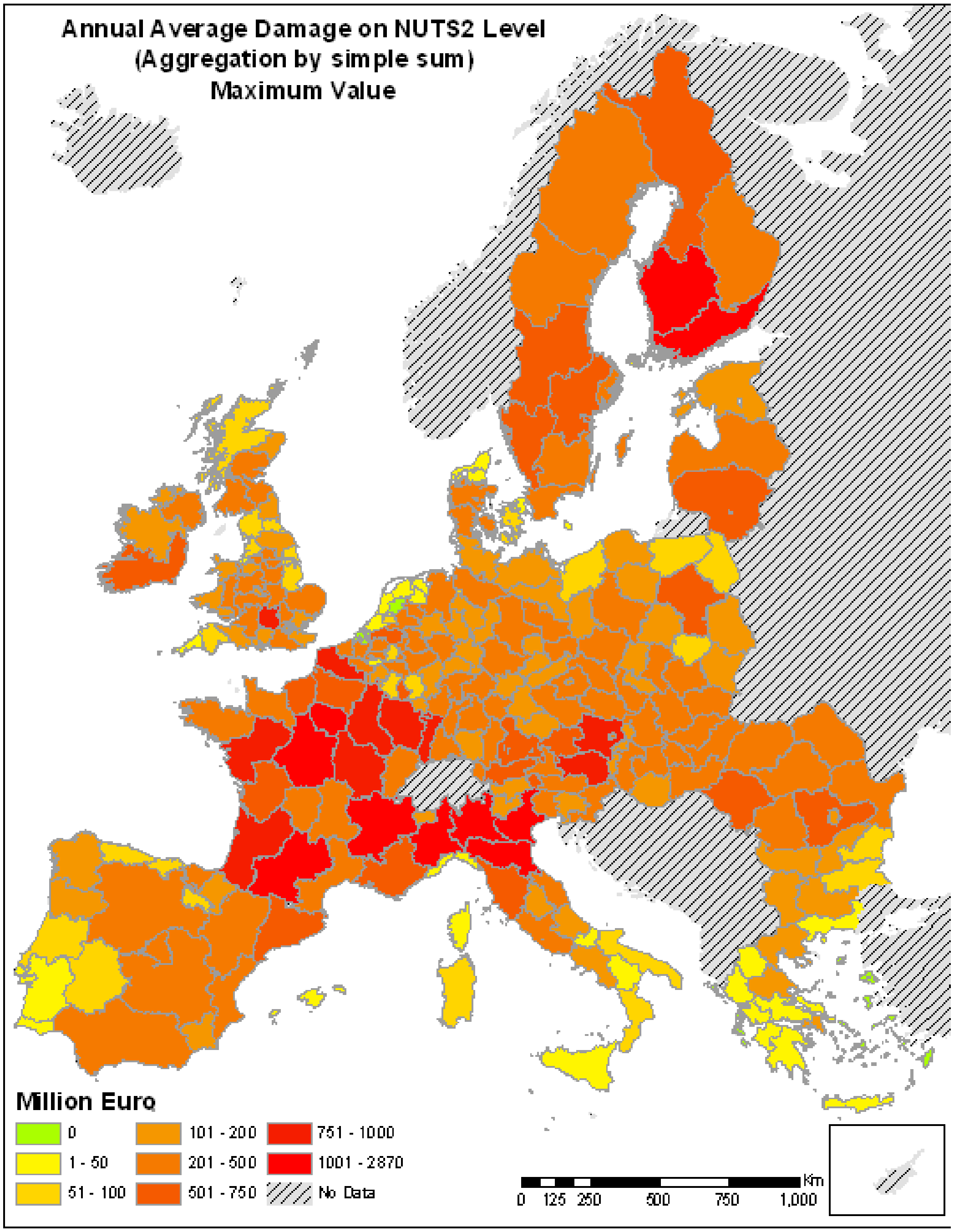
2.3.2 Maps of the expected damages from a 100-years flood: aggregation by hybrid convolution over NUTS2 regions

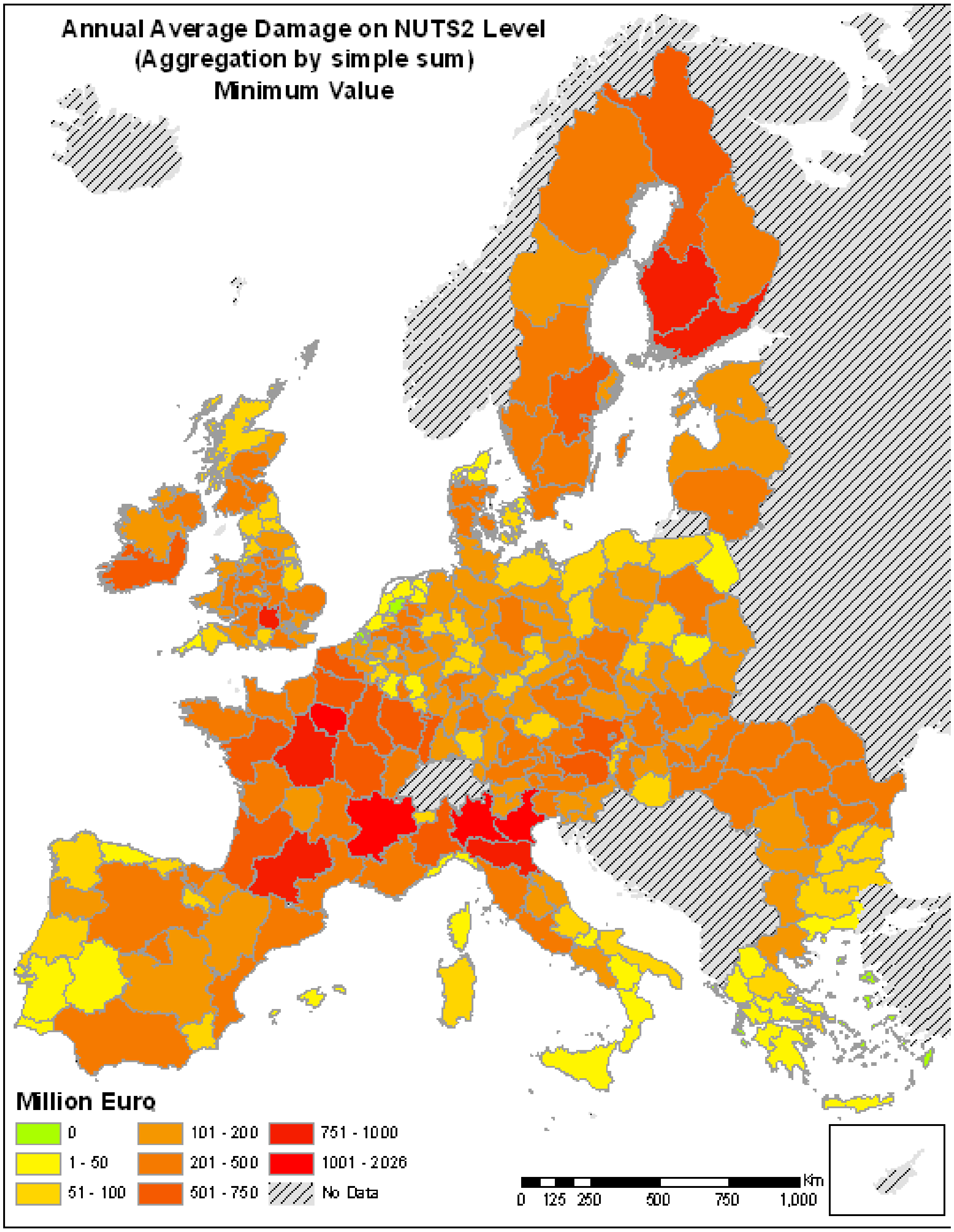


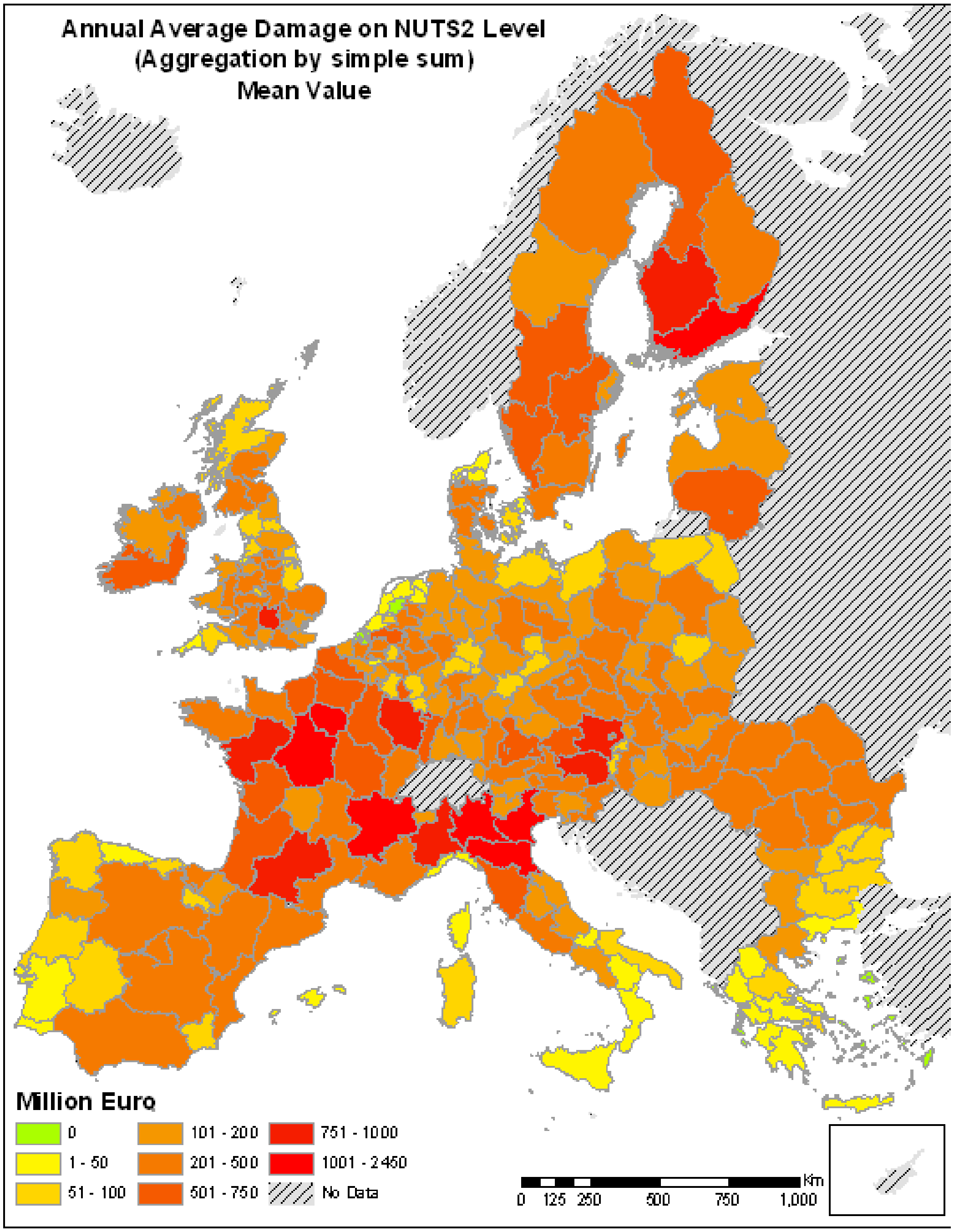

Damage from a 100-years flood on NUTS2 Level
(Aggregation by hybrid convolution)
Minimum Value
Billion Euro
0
< 0.5
0.5 - 1
1 - 2
2 - 5
5 - 7.5
7.5 - 10
> 10 (max value: 14)
No Data
Km
0 125 250 500 750 1,000


Damage from a 100-years flood on NUTS2 Level
(Aggregation by hybrid convolution)
Mean Value
Billion Euro
0
< 0.5
0.5 - 1
1 - 2
2 - 5
5 - 7.5
7.5 - 10
> 10 (max value: 14.5)
No Data
0 125 250 500 750 1,000
Km

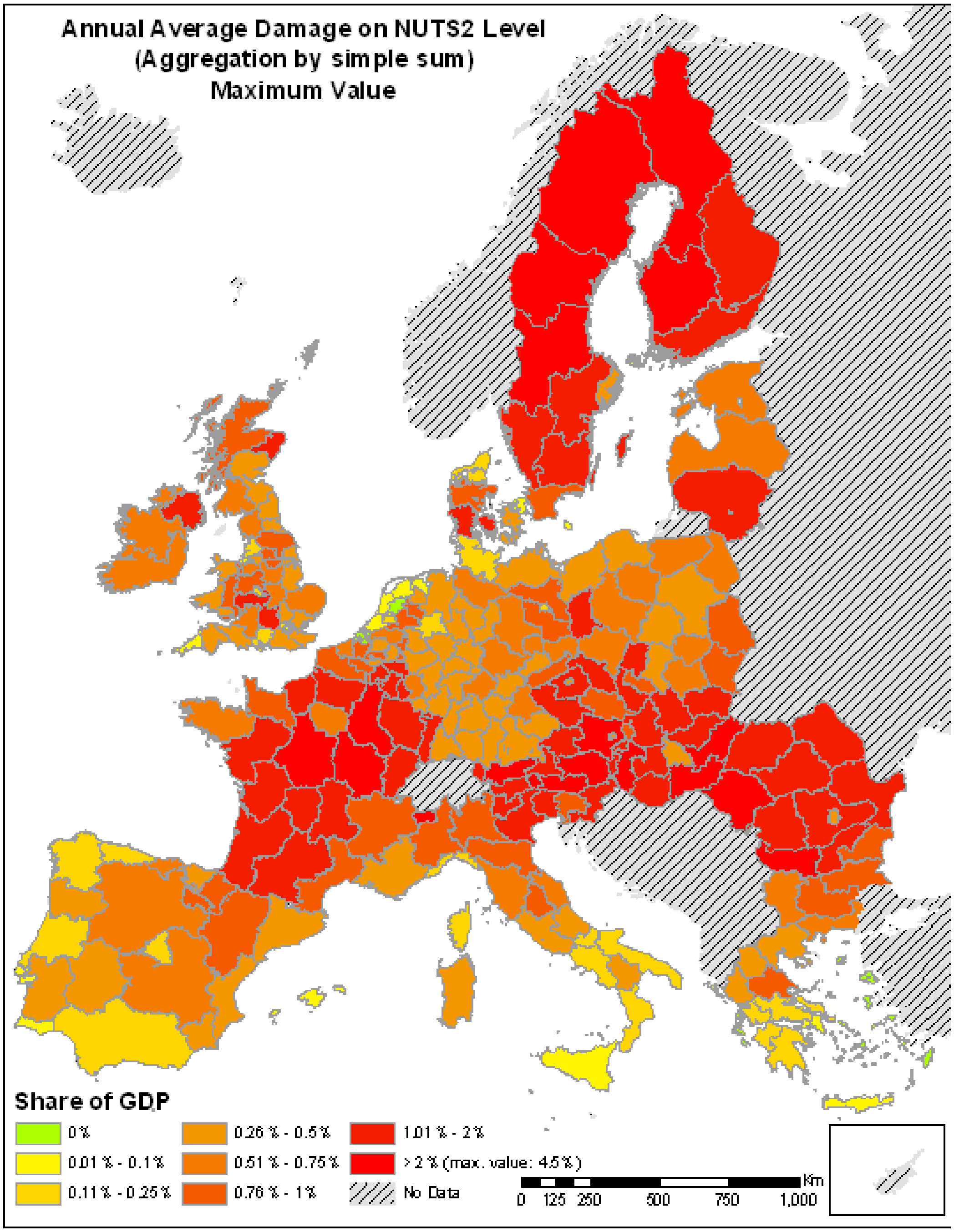
2.3.3 Maps of the annualized damages (Annual Average Damage – AAD) by absolute values: aggregation by simple summation over NUTS2 regions

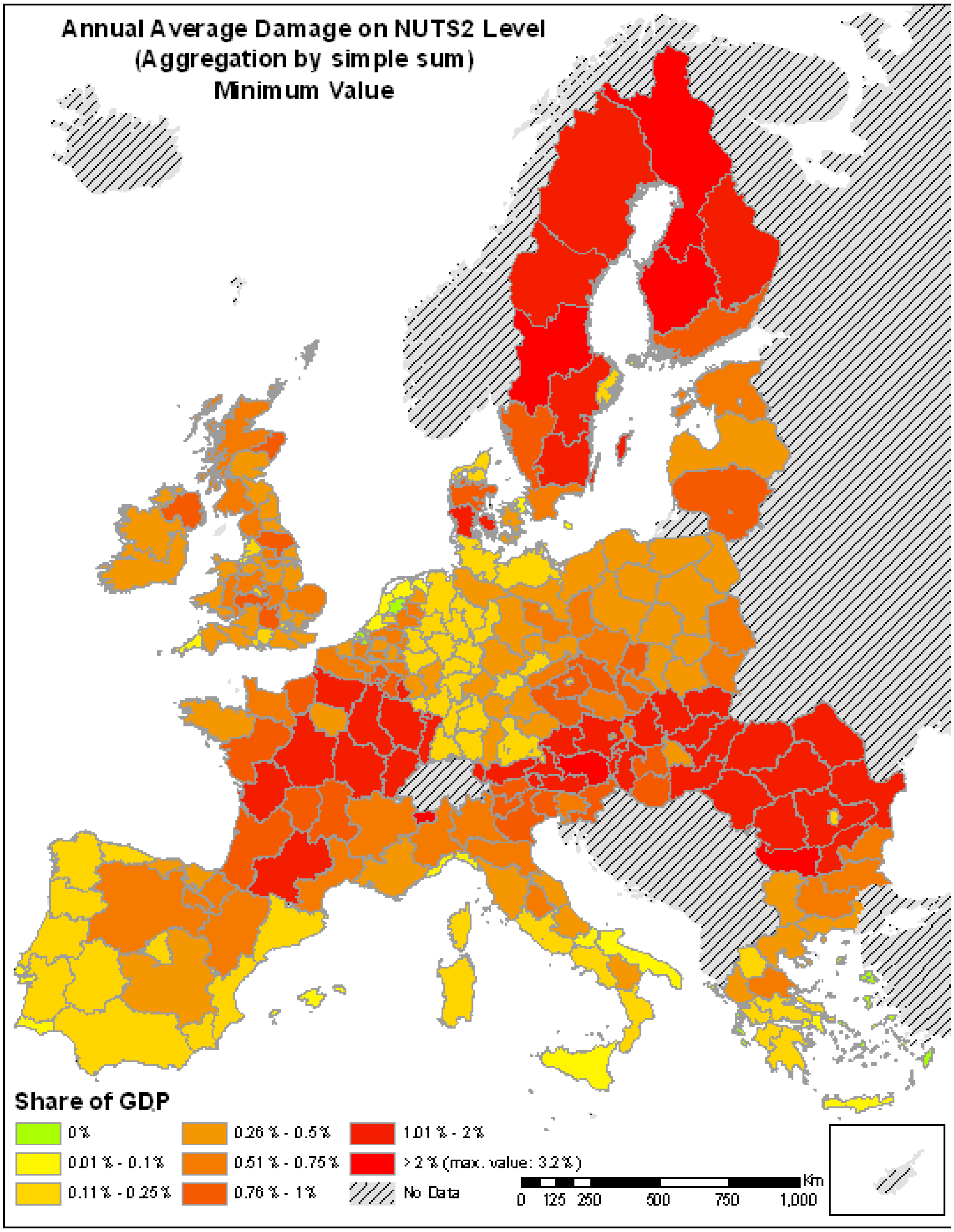


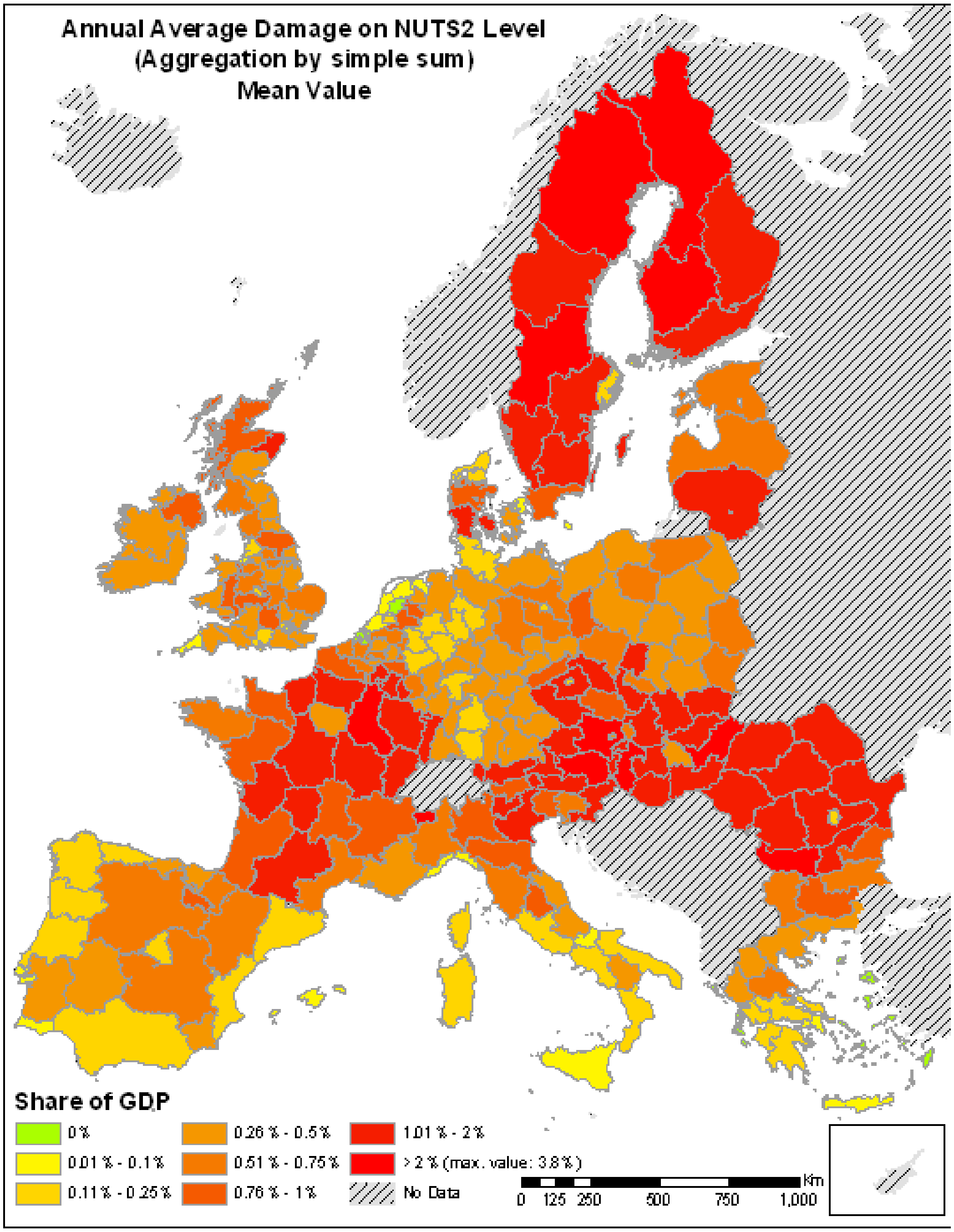

Annual Average Damage on NUTS2 Level
(Aggregation by simple sum)
Minimum Value
Million Euro
0
1 - 50
51 - 100
101 - 200
201 - 500
501 - 750
751 - 1000
1001 - 2026
No Data
Km
0 125 250 500 750 1,000


Annual Average Damage on NUTS2 Level
(Aggregation by simple sum)
Mean Value
Million Euro
0
1 - 50
51 - 100
101 - 200
201 - 500
501 - 750
751 - 1000
1001 - 2450
No Data
Km
0 125 250 500 750 1,000

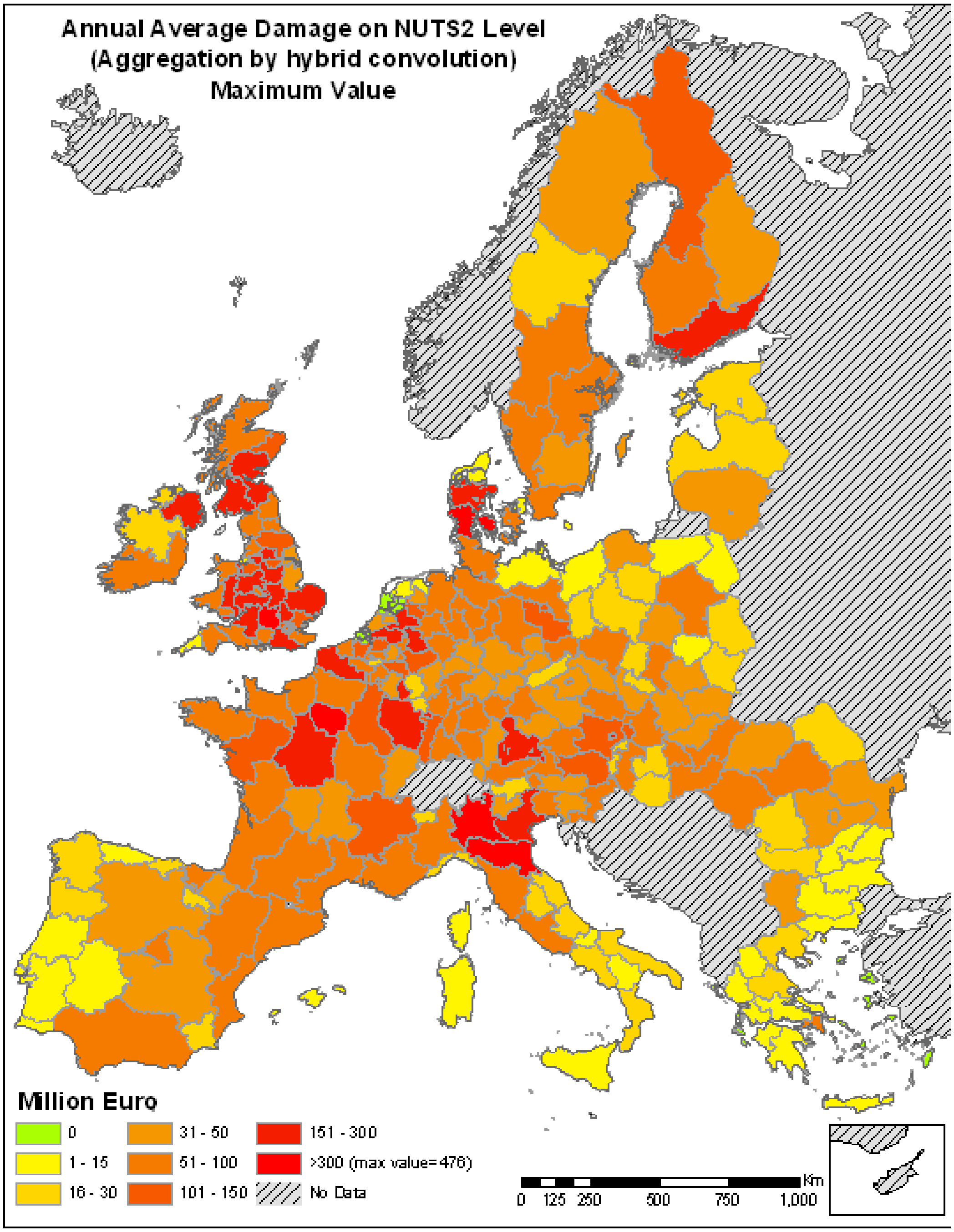
2.3.4 Maps of the AAD by share of GDP: aggregation by simple summation over NUTS2 regions

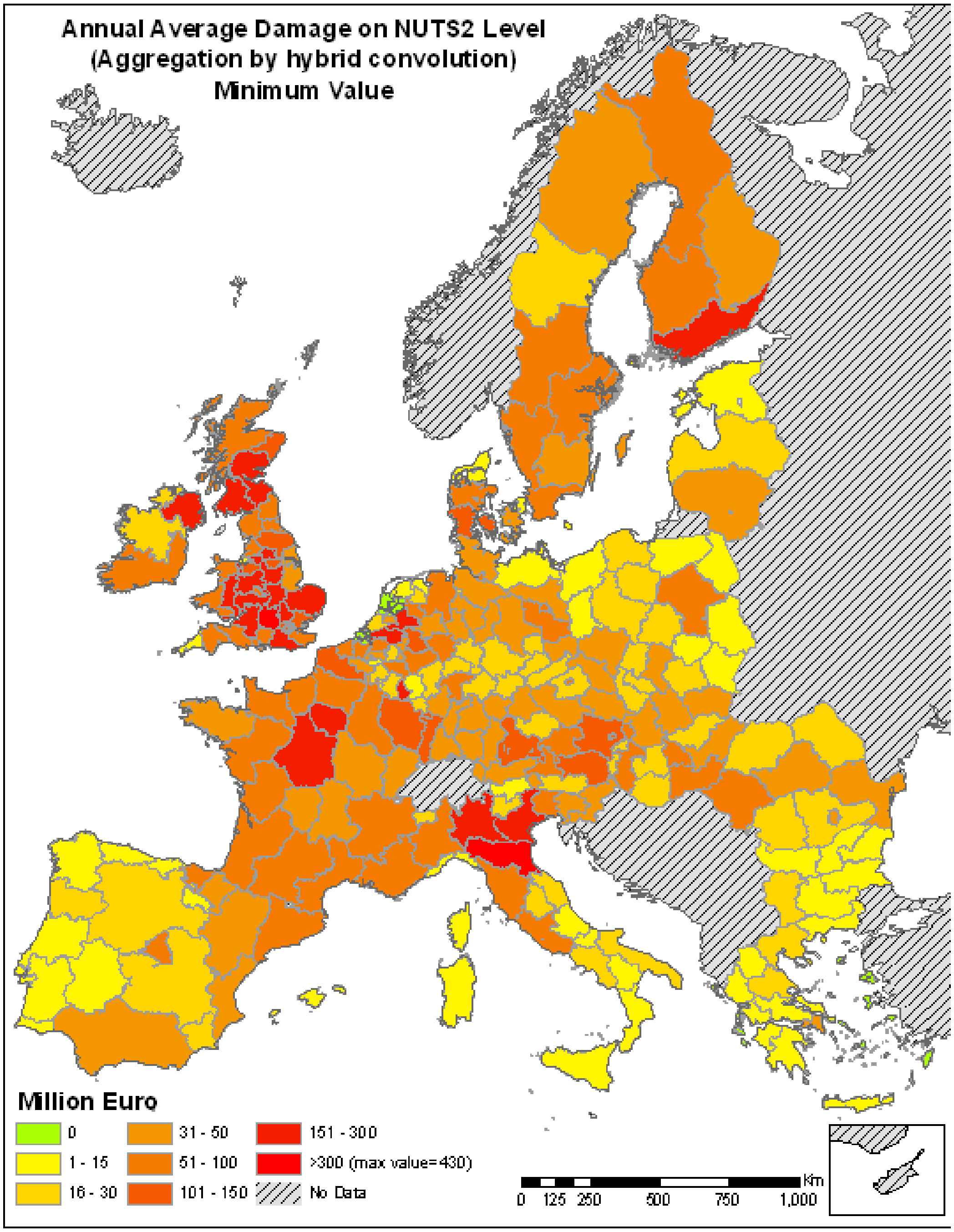


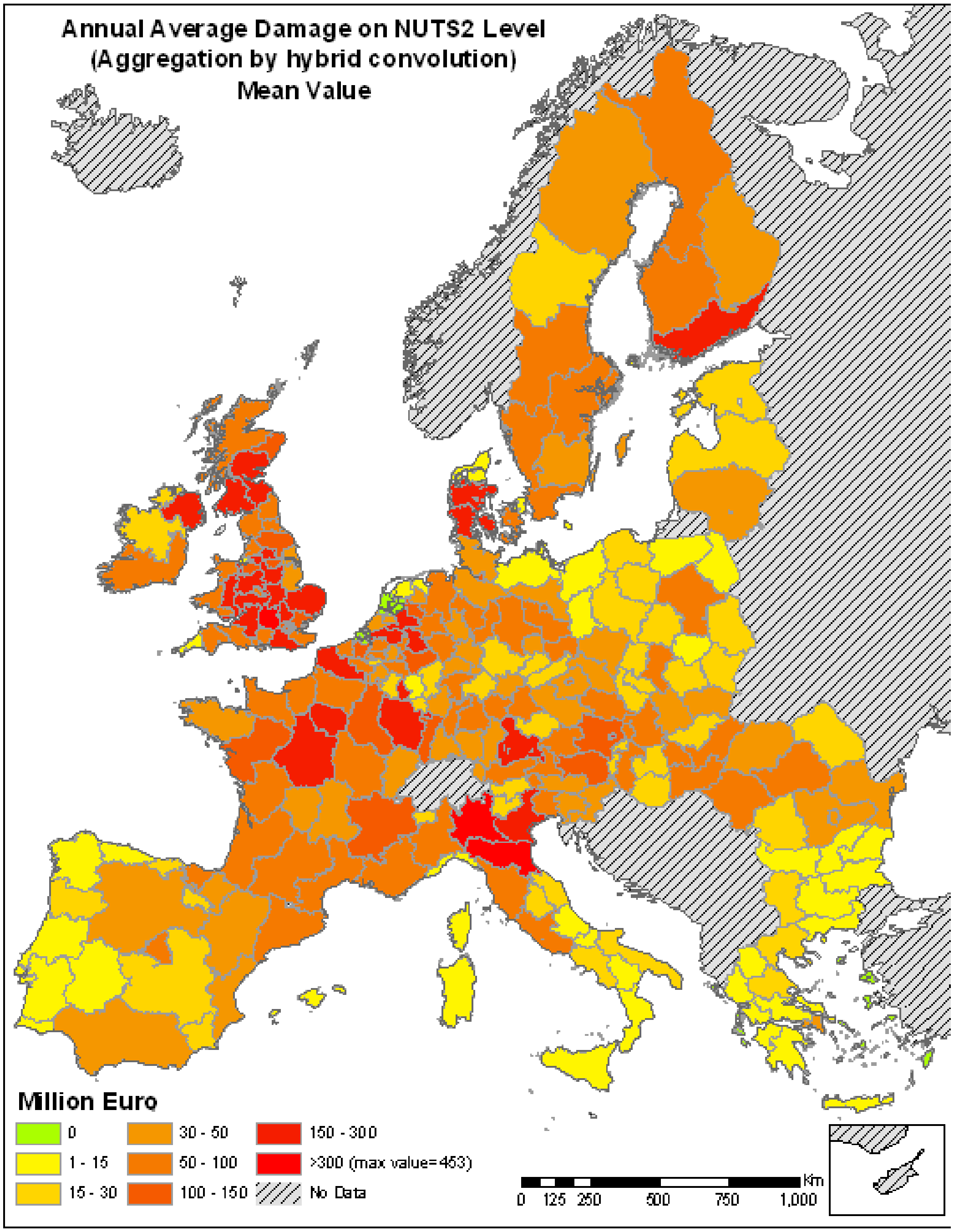

Annual Average Damage on NUTS2 Level
(Aggregation by simple sum)
Minimum Value
Share of GDP
0 %
0.01 % - 0.1 %
0.11 % - 0.25 %
0.26 % - 0.5 %
0.51 % - 0.75 %
0.76 % - 1 %
1.01 % - 2 %
> 2 % (max. value: 3.2 %)
No Data
0 125 250 500 750 1,000
Km


Annual Average Damage on NUTS2 Level
(Aggregation by simple sum)
Mean Value
Share of GDP
0 %
0.01 % - 0.1 %
0.11 % - 0.25 %
0.26 % - 0.5 %
0.51 % - 0.75 %
0.76 % - 1 %
1.01 % - 2 %
> 2 % (max. value: 3.8 %)
No Data
Km
0 125 250 500 750 1,000

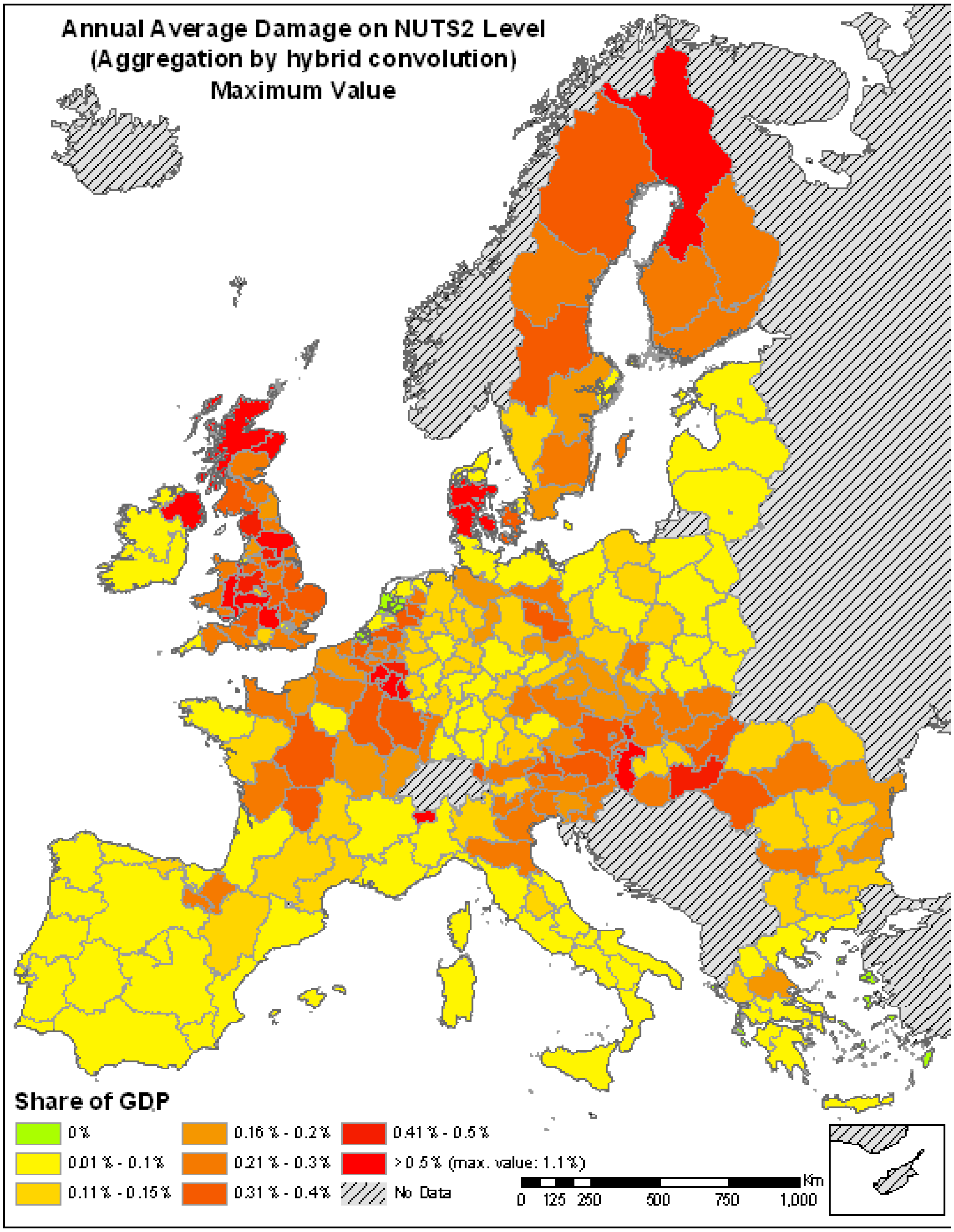
2.3.5 Maps of the AAD by absolute values: aggregation by hybrid convolution over NUTS2 regions

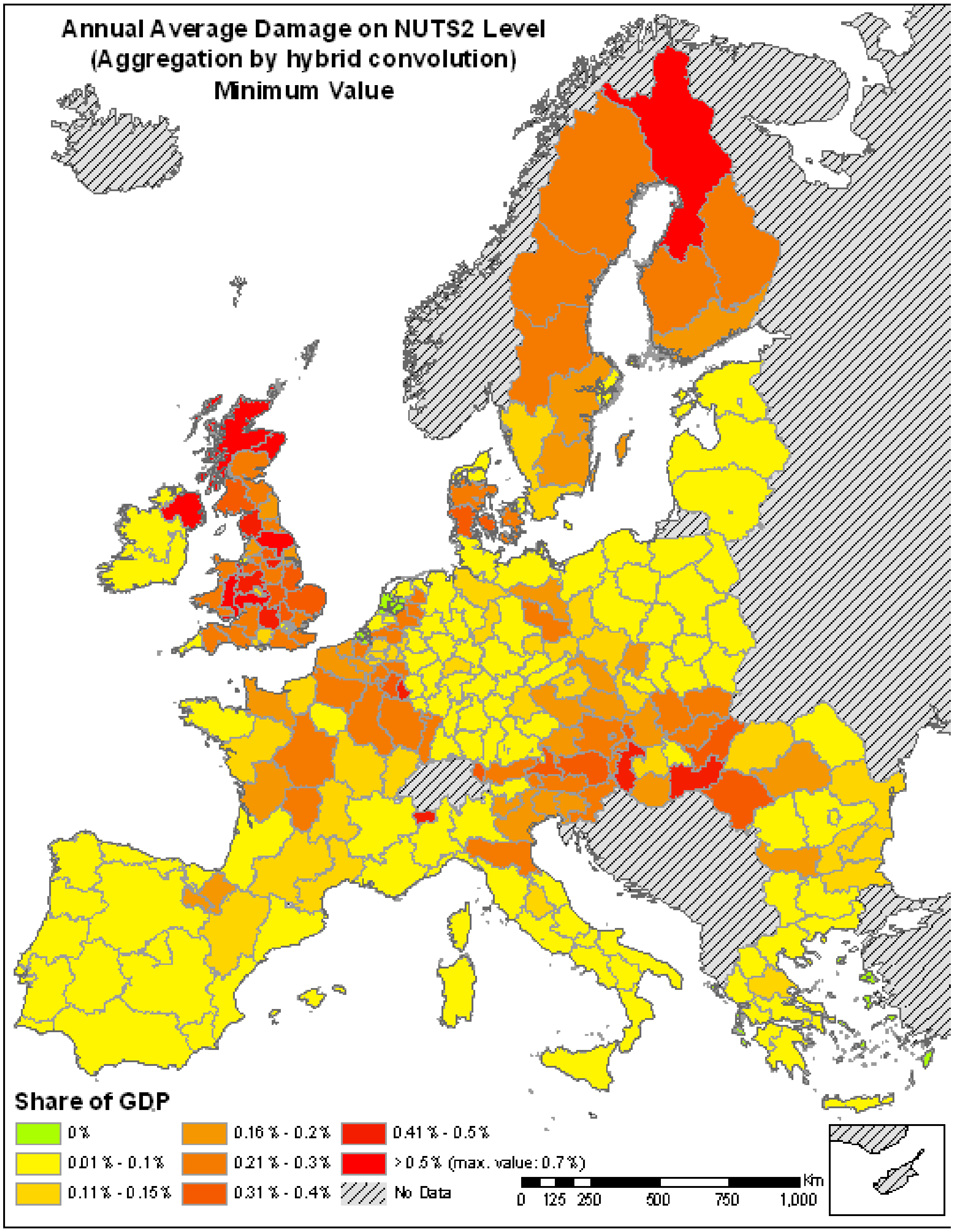


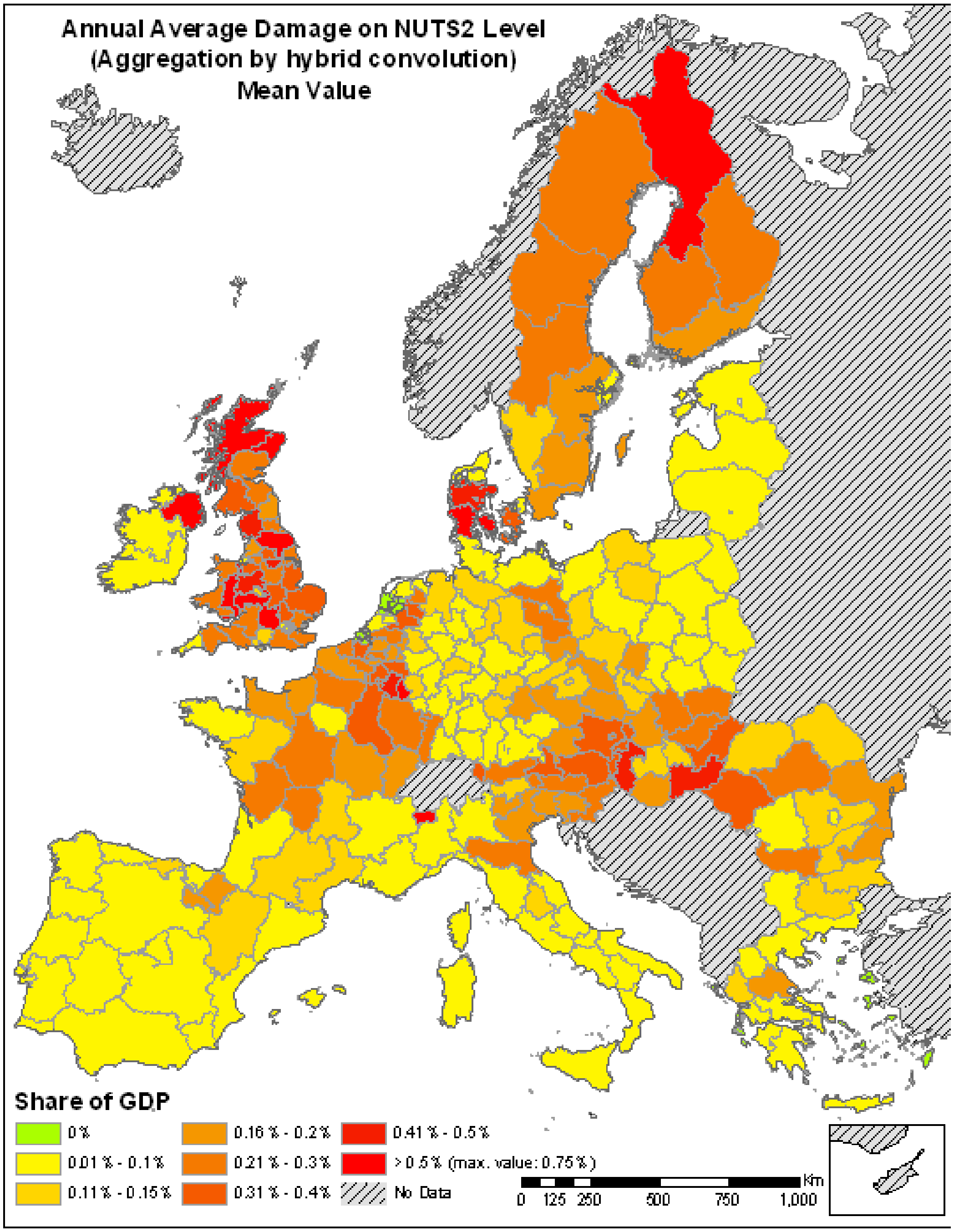

Annual Average Damage on NUTS2 Level
(Aggregation by hybrid convolution)
Minimum Value
Million Euro
0
1 - 15
16 - 30
31 - 50
51 - 100
101 - 150
151 - 300
>300 (max value=430)
No Data
Km
0 125 250 500 750 1,000


Annual Average Damage on NUTS2 Level
(Aggregation by hybrid convolution)
Mean Value
Million Euro
0
1 - 15
15 - 30
30 - 50
50 - 100
100 - 150
150 - 300
>300 (max value=453)
No Data
km
0 125 250 500 750 1,000

2.3.6 Maps of the AAD by share of GDP: aggregation by hybrid convolution over NUTS2 regions




Annual Average Damage on NUTS2 Level
(Aggregation by hybrid convolution)
Minimum Value
Share of GDP
0 %
0.01 % - 0.1 %
0.11 % - 0.15 %
0.16 % - 0.2 %
0.21 % - 0.3 %
0.31 % - 0.4 %
0.41 % - 0.5 %
> 0.5 % (max. value: 0.7 %)
No Data
Km
0 125 250 500 750 1,000


Annual Average Damage on NUTS2 Level
(Aggregation by hybrid convolution)
Mean Value
Share of GDP
0 %
0.01 % - 0.1 %
0.11 % - 0.15 %
0.16 % - 0.2 %
0.21 % - 0.3 %
0.31 % - 0.4 %
0.41 % - 0.5 %
> 0.5 % (max. value: 0.75 %)
No Data
Km
0 125 250 500 750 1,000

3 Drought/Heat risk

3.1 Introduction

Since agricultural practices are climate-dependent and yields vary from year to year depending on the weather, agricultural sector is particularly exposed to changes in climatic mean values and variability. Additionally, the agricultural sector represents the major land use across the globe and consequently is the major economic, social, and cultural activity, providing a wide range of ecosystem services. The summer heat wave of 2003 (Schär et al. 2004), taken as an indicator of the future climate change, accompanied by precipitation deficits, has led to agricultural damages of more than €13 billion, 30% reduction in gross primary production of terrestrial ecosystems, numerous and extensive wild fires (390,000 ha in Portugal), and problems in water supply and energy production (IPCC, 2007). In Poland, the six-week (mid-June to end of July) period of deficient precipitation in 2006 caused high agricultural damage.

As a consequence, understanding the potential impacts on agriculture of climate change in general and increasing climate extreme events in particular has become increasingly important and is of main concern especially for the sustainability of agricultural system and for policy-making purposes.

3.2 Application of the risk triangle to crop yield

The implementation of the risk-triangle methodology defined in section 1 applies to the damage assessment in agriculture, according to the scheme of Fig. 3.1a, with the following specifications:

Exposure is interpreted as the areas where cultivation is present and its actual economic value. In other words, it depends on land use (type of crop) and the monetary value of that crop. This could be measured as the product of the simulated average yield of each crop by the price that is actually paid per ton. Maps of yield of different crops including maize, wheat, sorghum and barley were produced for the present period (1960-1990) and the monetary value of each crop was assessed on the basis of average yield for 30 years and the average producer price. CLC and EUROSTAT/FAOSTAT crop statistics has been used in this context.

Vulnerability here measures the extent to which the subject matter could be affected by the hazard. In other terms, it describes the degree of coupling (impact) between exposed crops and extreme events (heat waves and water stress) occurring during the growing season. Since crop sensitivity to extreme events is phenological-stage dependent, only extreme events occurring at more sensible phenological stages will be considered. In particular, heat stress or drought, occurring at anthesis stage were indicated as the most detrimental for crop yield. Vulnerability is expressed as the fraction of yield loss for the different return period (potential-actual yield).

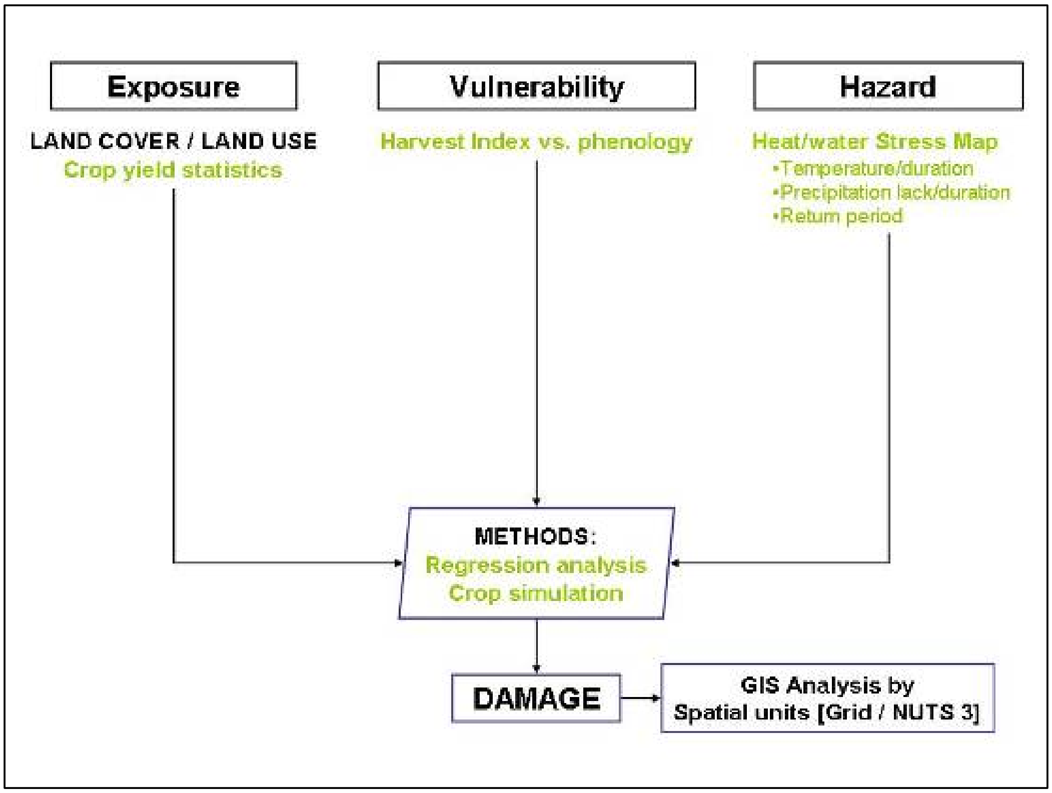


***Figure 3.1a**: Application of the risk triangle to crop yield.*

Hazard is the probability of occurrence, which is related to the climate of an extreme event which, in turn, causes an impact on the growing plants. The investigation of extreme events and their parameterisation in terms of probability of occurrence (or return periods) was performed through the analysis of observed events having impact on agriculture.

The Cropsyst model has been used to assess crop yield on the basis of HadCM3 empirical downscaling at a resolution of 50x50Km over Europe for baseline and for SRES scenarios A2 corresponding at a climatic window of +2°C with respect to pre-industrial period. This procedure is fully described in the final report of WP A2.2 As concerning crop growth, extreme events having higher impact on final yield will be taken into account in this work, namely heat waves and water stress at anthesis stage.

Figure 3.1.b shows the basic flow diagram of the implementation of the "risk triangle" methodology.

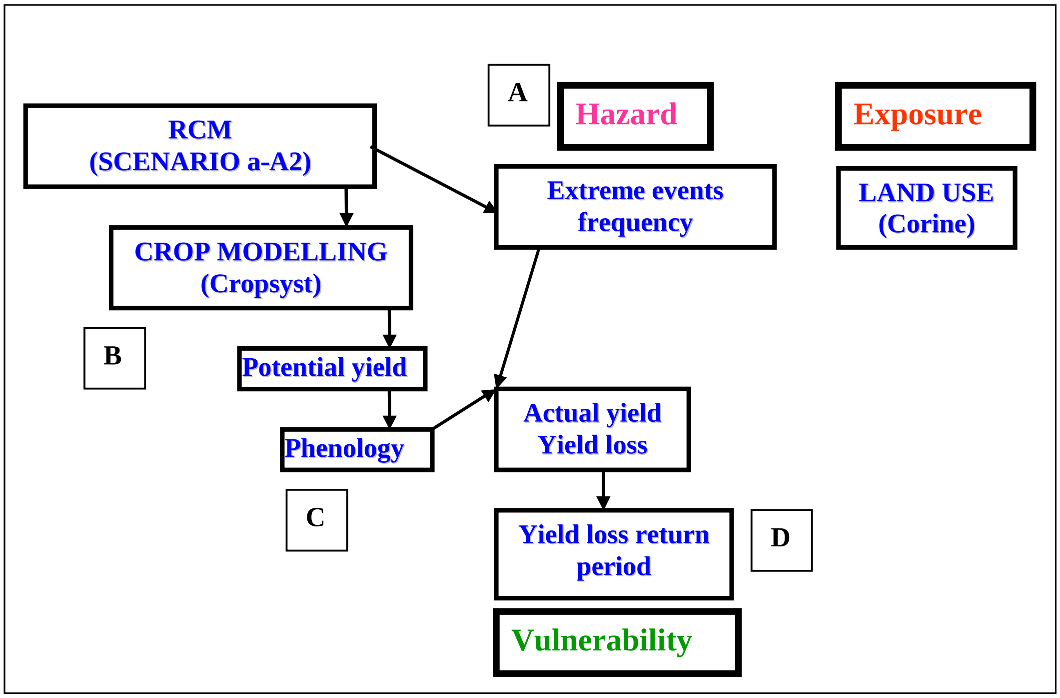


***Figure 3.1b**: Flow diagram of risk triangle implementation for climate change impact assessment on agriculture. First stage: use of climate data for extreme events frequency calculation (A). Second stage: use of climate data as crop growth simulation model to simulate potential yield (not including extreme events impact) and phenological stages (B). Intersection of extreme events frequency information to phenological stages dates to assess number and intensity of extreme events occurring at anthesis stage (C). Assessment of yield loss and its return period over 30 years (D) and overlay to the exposure map.*

3.3 Crop modelling

CropSyst is a multi-year, multi-crop, daily time-step crop-growth simulation-model. It simulates soil-water budget, soil-plant nitrogen budget, crop canopy and root growth, phenology, dry matter production, yield, residual production and decomposition, and erosion. The user can input management parameters such as sowing date, cultivar genetic coefficients (photoperiodic sensitivity, duration of grain filling, maximum LAI, etc.), soil profile properties (soil texture, thickness), fertilizer and irrigation management, tillage, atmospheric CO_2 concentration etc.

The simulation of crop development in CropSyst is mainly temperature-dependent and it is based on the thermal time required to reach specific development stages. Thermal time is calculated as growing degree-day (GDD, °C day^{-1}) defined as the sum of differences between the average of the daily maximum and minimum temperatures and a base temperature, usually 10 °C, accumulated throughout the growing season (starting from sowing until harvest, cf *http://en.wikipedia.org/wiki/Growing_degree_day*). Average air temperatures above a base temperature and below a cut-off temperature are considered for GDD calculation. In the simulation of crops development also other environmental aspects, such as day-length, low temperature requirements, i.e.vernalization and soil water content, are taken into consideration. In particular for winter crops the vernalization process provides the exposure to low, non-freezing temperatures to enter the reproductive stage and GDD accumulation is limited until vernalization requirements are met. In post-vernalization phase, longer days increase linearly the development rate in the range between 8-15 h. the phenology of summer crops such as maize, soybean and sunflower is only temperature dependent with no vernalization requirements.

The core of the model is the determination of the biomass potential growth under optimal conditions (without water-nitrogen stress) based both on crop potential transpiration and crop intercepted photosynthetic active radiation. The potential growth is then corrected by water and nitrogen limitations, if any, and the actual daily biomass gain is thus determined. The simulated yield is obtained as product of the actual total biomass cumulated at physiological maturity and the Harvest Index (HI = harvestable yield/above-ground biomass).

Furthermore, the use of a modified version of the model allowed considering the effect of increasing atmospheric CO_2 concentration on potential evapotranspiration, crop Water Use Efficiency (WUE, [Kg m^{-3}]) and Radiation Use Efficiency (RUE, g MJ^{-1}), cf. Tubiello et al. (2000).

3.4 Heat and drought stress impact

In CropSyst, drought stresses occurring at anthesis and grain filling period are already considered as yield-reducing factors. A mean water stress index (ranging from 0 [no stress] to 1 [maximum stress]) is calculated during these reproductive stages and used to proportionally decrease the harvest index according to equation:

$$WSF=(1-AvStress_a)*(1- AvStress_{gf}) \quad (1)$$

Where WSF is the water stress factor which ranges from 1 (any water stresses neither during anthesis [$AvStress_a$] or grain filling [$AvStress_{gf}$]) to 0 (at least a maximum water stress during anthesis or grain filling).

By contrast, CropSyst, like other widely used models, does not include the simulation of heat stress on final yield. This results in a potential underestimation of climate change impact in agriculture (Porter and Gawith, 1999) since heat stresses at anthesis have been widely demonstrated to be a yield reducing factor (Challinor et al. 2005).

In this work, heat stress impact on final yield was introduced into CropSyst model after the approach proposed by Moriondo et al. (2009b). This model relies on the simulation of final HI as function of the Grain Filling duration (GF, expressed as the number of days from fruit-set to maturation) and the daily increase of HI (dHI/dt, provided that it is constant during the whole GF [Bindi et al., 1999]). Accordingly:

$$HI = {dHI}/_{dt} \times GF \quad (2)$$

The approach proposed by Challinor et al (2005) and adapted to CropSyst by Moriondo et al. (2009), was then used to calculate the impact of heat stress events on dHI/dt during anthesis for winter and summer crops. Such episodes were identified by comparing the T_{max} to a critical value T^{cr}_{min}, above which grain-set starts to be reduced up to the minimum level corresponding to a severe heat shock (T_{lim}, the temperature at 0% grain-set).

For both type of crops high temperature episodes during pre- and post-anthesis were demonstrated to decrease grain-set (Porter and Gawit, 1999; Chimenti and Hall, 2001). Accordingly, a period included between –5 to +8 days from full anthesis date was assumed as sensitive to the effect of heat stress (Tashiro and Wardlaw, 1990). with T_{cr}=31°C and T_{lim}=40°C at full anthesis (Narciso et al., 1992).

The heat stress impact on dHI/dt was calculated by:

$$\frac{dHIa}{dt} = \frac{dHIu}{dt} \times \left[1 - \frac{(Pcr - Ptot)}{Pcr}\right] \qquad \text{for } P_{tot}<P_{cr} \qquad (3)$$

where P_{tot} is the relative grain-set (ranging from 0 to 1), P_{cr} is the critical fractional grain-set below which dHI/dt begins to be reduced from its non-stressed value (dHI_u/dt) to the actual value (dHI_a/dt.). For both crop type, the same critical fractional grain-set (P_{cr}=0.85) was assumed.

Final HI was then calculated as the product of the obtained dHI_a/dt and GF and it was decreased by the effect of drought stress as calculated by Cropsyst (WSF). Yield was then recalculated as the product of the resulting HI and the total above ground biomass (AGB) as simulated by CropSyst.

$$\text{Yield=AGB x dHIa/dt x WSF x GF} \qquad (4)$$

The number of heat stress events was accordingly computed for each crop in a period including pre and post anthesis, where the impact of temperature is higher. The crop included in this analysis may have different sensitivity to heat stress but generally the maximum tolerance threshold ranges between 31°C-33°C. The impact of heat stress on yield, calculated according the equation 2, was averaged over the period 1975-2005.

Drought stress events were derived directly from Cropsyst model, driven by the results of the downscaled HadCM3 GCM for the present period. The model includes subroutines simulating soil water content for each soil layer (equation 1) and the number of events per year was averaged over the period (1975-2005). The model computed potential and actual yield of winter crops (barley) and summer crops (sunflower, maize, sorghum, soybean). All the grid points included in the dataset were used for crop growth simulations. All the pixels where the growing cycle was not completed by Cropsyst (i.e. a complete simulation from sowing to harvest time) were discarded so that the maps presented may be intended as potential cultivated areas of each crop.

The model was also run for future scenarios. According to the division of the work designed in the WP's, maps of future trends, along with those representing the effect of different adaptation practices, are included in the final report of WP A.2.2. Next section reports the maps for present scenario as baseline condition to assess both climate change and adaptation measures.

3.5 Results and maps

It's not straightforward to have the drought analysis only focused on today's risk as it is very much integrated with climate modelling, so that also comments on baseline maps are complicated.

In any case, this analysis allowed to distinguish the relative importance of heat waves and water stress as crop yield reducing factors. The results indicated that, in present conditions, water stress represents the most limiting factor reducing potential yield, and this is especially true over the Mediterranean basin. The relative importance of heat waves in affecting yield is in fact very low. Summer crops such as sorghum and maize were highly affected by heat waves/water stress whereas the impact of these reducing factor was much lower especially for barley which is a winter crop partially escaping the risk of higher temperatures and water stress in summer.

3.5.1 Average yield loss due to extreme events (heat stress and water stress) at anthesis stage

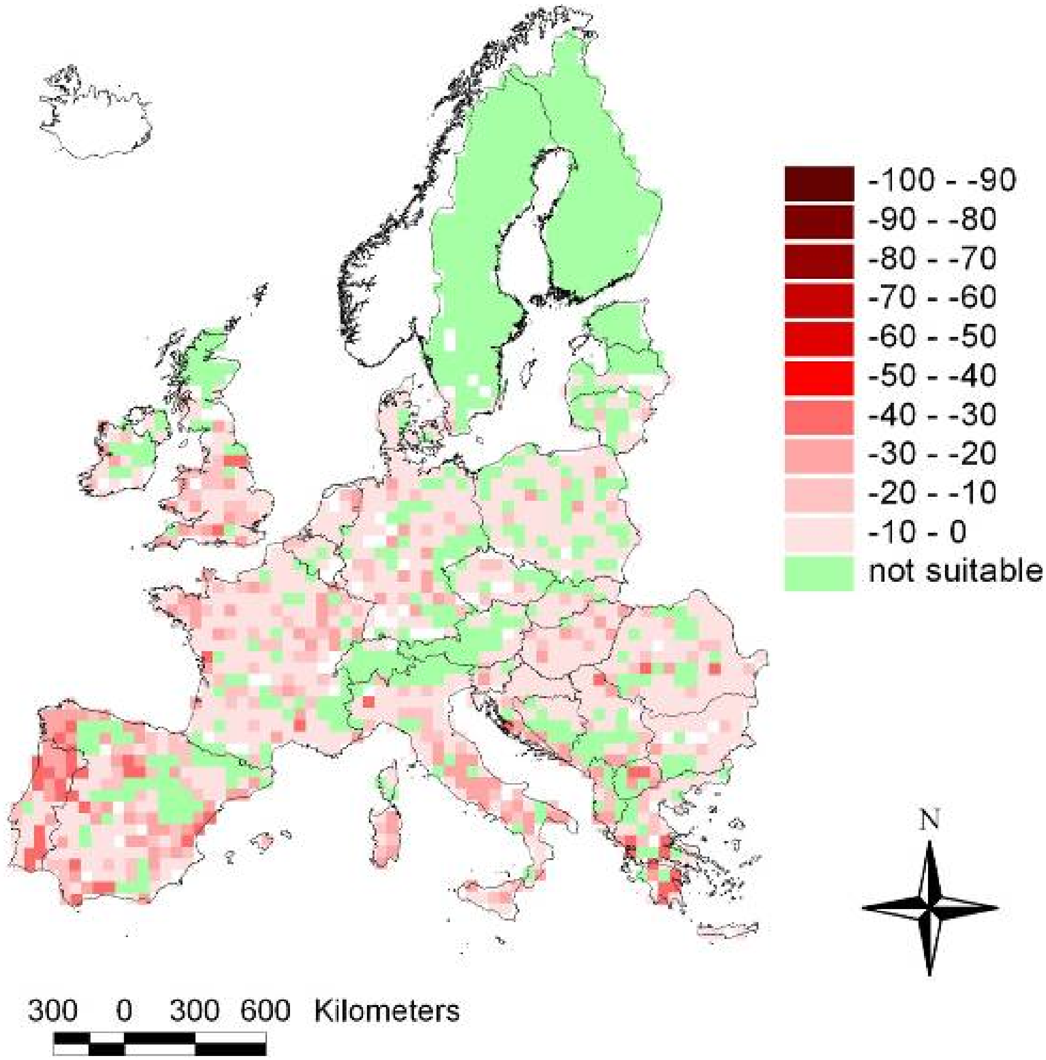


***Figure 3.2**: Barley. Yield loss due to both heat stress and heat events at anthesis expressed as percentage on potential biomass (average over 30 year)*

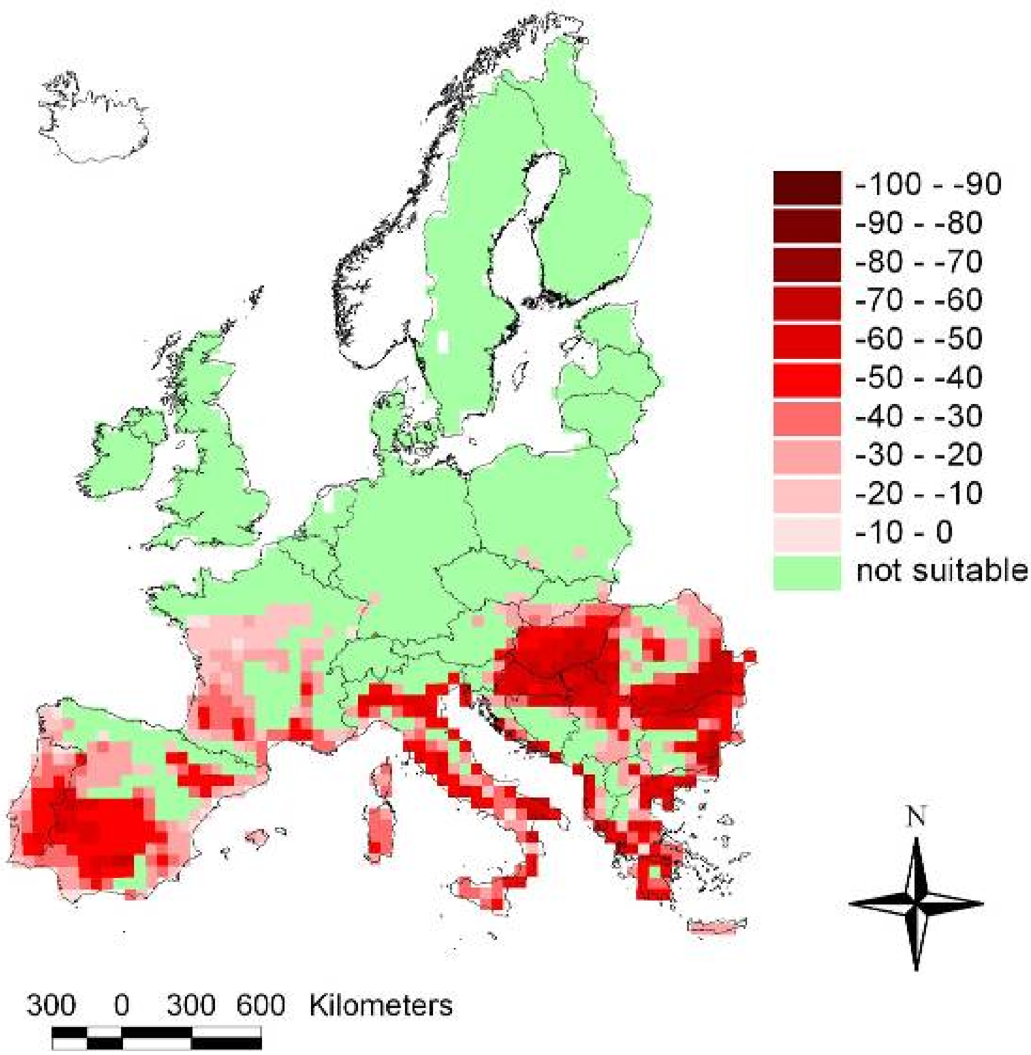


Figure 3.3*: Maize. Yield loss due to both heat stress and heat events at anthesis expressed as percentage on potential biomass (average over 30 year)*

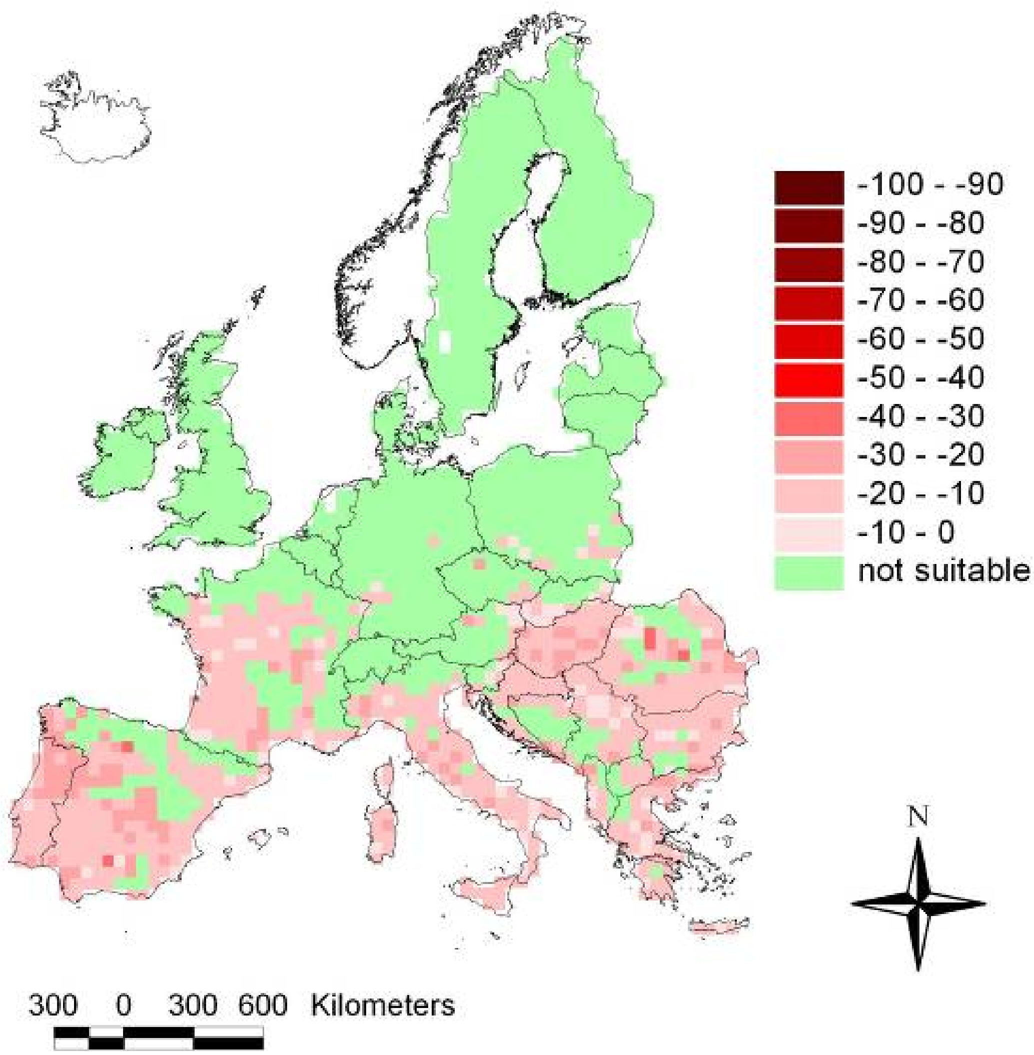


***Figure 3.4**: Sunflower. Yield loss due to both heat stress and heat events at anthesis expressed as percentage on potential biomass (average over 30 year)*

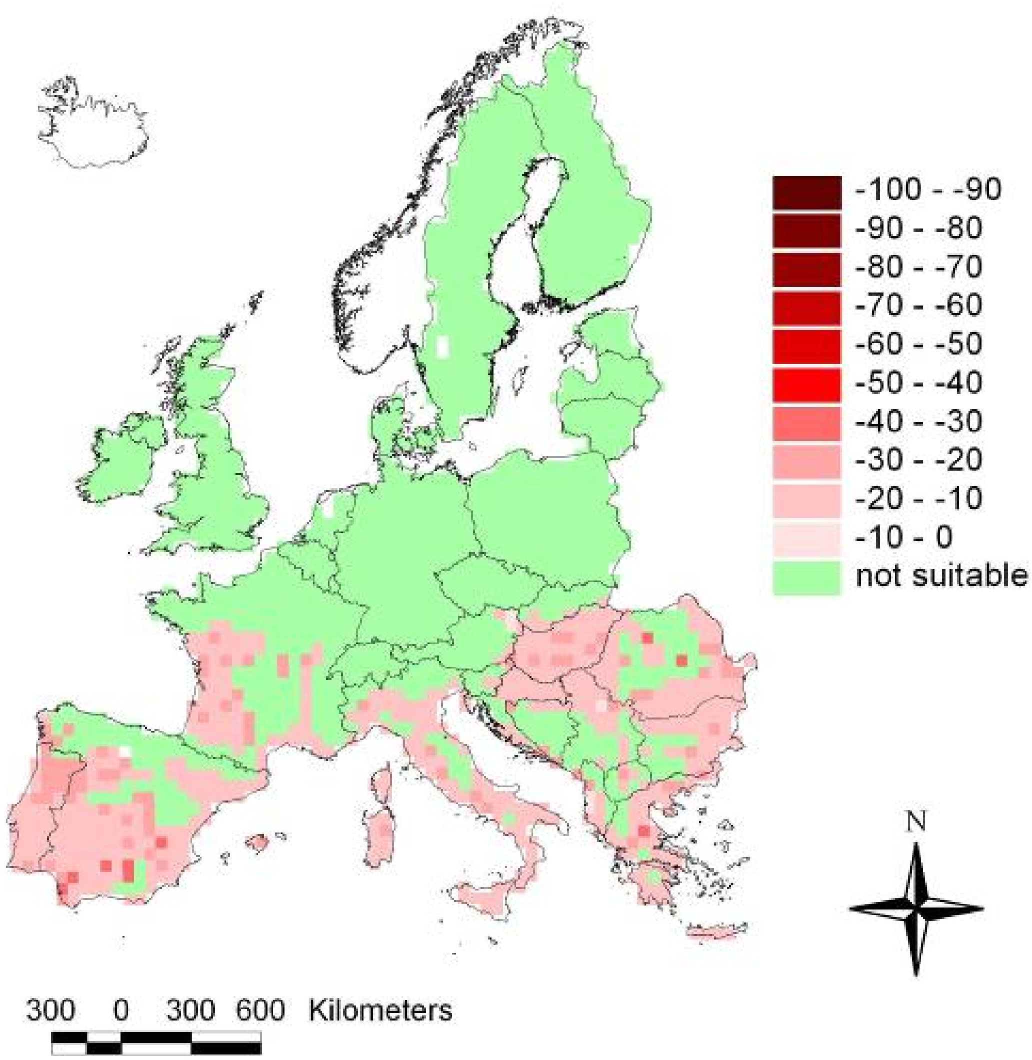


Figure 3.5*:Soybean. Yield loss due to both heat stress and heat events at anthesis expressed as percentage on potential biomass (average over 30 year)*

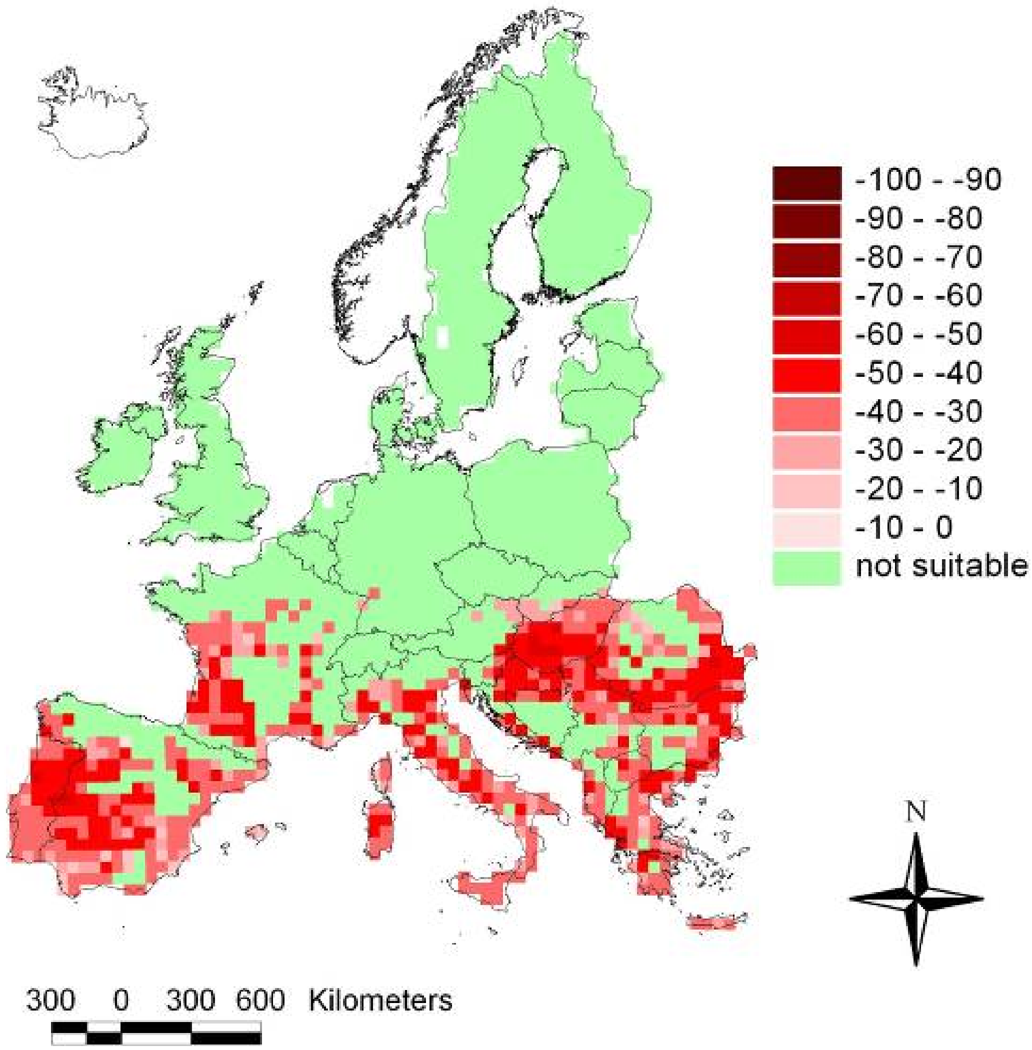


Figure 3.6*: Sorghum. Yield loss due to both heat stress and heat events at anthesis expressed as percentage on potential biomass (average over 30 year)*

4 Windstorm and fire risk in forests

4.1 Introduction

European forests are among the most intensively managed forests in the world. Despite their intensive use, the forest resources in Europe are growing. The forest area is currently increasing by about 760 thousand ha per year (0.4%; FAO 2007) and the average growing stock volume increased from 124 m^3 ha^{-1} in 1990 to 141 m^3 ha^{-1} in 2005 (FAO 2007). These trends are projected to continue for at least several decades to come (Schelhaas et al. 2006). Although these are positive trends, there are other developments that are cause for concern. One of these worrying developments is the occurrence of natural disturbances (FAO 2007). Several severe storms hit the European forests over the last decade, causing unprecedented damage (Schelhaas et al. 2003). In the Mediterranean basin, fire is the major disturbance factor. Annually (average 1980-2007) more than 50 thousand fires burn an area of almost 0.5 million ha (JRC, 2008). Damage due to disturbance agents like storms and fire seems to be increasing over Europe over the last decades (Schelhaas et al. 2003). Changes in the state of the forest, changes in the way forests are managed and changes in the climate are thought to have contributed to this increase (Schelhaas et al. 2003). Climate models project worsening fire weather conditions for the future and possibly more frequent and more intensive storms (Alcamo et al., 2007). Combined with expected increases in forest area and standing wood volumes in the forest (Schelhaas et al. 2006; Nabuurs et al. 2007), a future increase in damage due to these disturbance agents seems inevitable. As mentioned in the executive summary, the part of this work focused on future trends is included in the final report of WP A.2.2. Here we show how the “risk triangle” approach has been implemented on fire and wind damage to forests in Europe from the analysis of historic drivers and their correlation with occurrence patterns.

4.2 Method

Similarly to the natural hazards treated in the previous chapters, the approach has followed the scheme here reported in fig. 4.1.

For forest fires, the hazard depends for a large part on weather conditions, as it is increased by factors as high temperature, lack of precipitation and presence of wind. The Fire Weather Index (FWI) as developed by the Canadian Forest Service is an example how the effect of weather conditions on fire hazard can be summarised (Van Wagner 1987). It is a daily meteorology-based index, used worldwide to estimate fire danger in a generalized fuel type. FWI consists of six standard components each measuring a different aspect of fire danger (Van Wagner 1987). Three components represent daily changes in the moisture contents of three classes of forest fuel with different drying rates (light, intermediate and heavy fuels). The other three components are related to the fire behaviour representing the rate of spread, fuel weight consumed and fire intensity. The system depends solely on weather readings taken each day at noon: temperature, relative humidity, wind speed and rainfall. In addition, the current month must be specified. Several studies showed that the FWI system and its components were well suited for the estimation of fire risk for the Mediterranean basin (Aguado et al. 2003, Viegas et al. 1999, Viegas et al., 2001, Sol 1999). We therefore take the FWI value in June, July and August as an indication for the fire hazard.

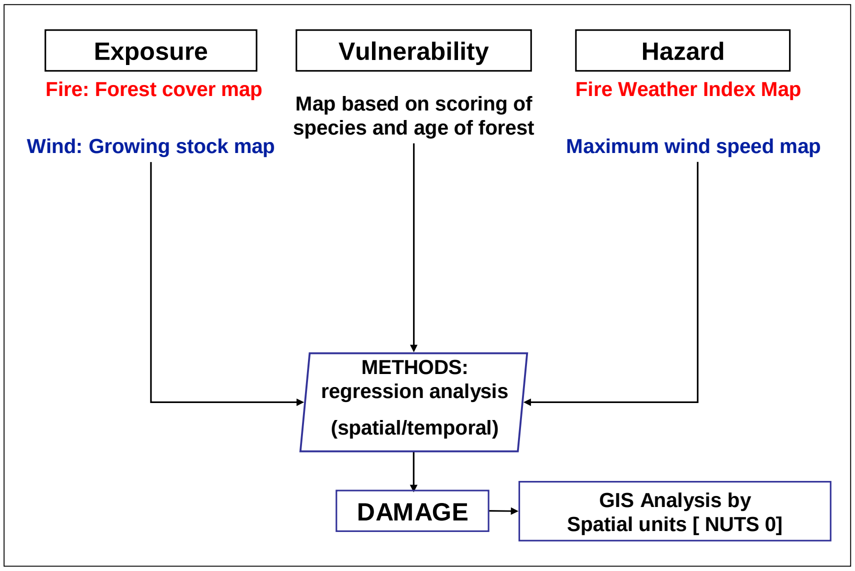


Figure 4.1: *Application of the risk triangle to forest fires and windstorms (red: fires; blue: windstorms; black: common).*

The hazard from wind is entirely related to the wind climate. European countries with Atlantic coastlines generally experience higher wind speeds, with Ireland and the United Kingdom in particular having a rather severe wind climate. Also, mountainous regions generally experience a more severe wind climate due to topographical influences. Wind speeds are usually presented as hourly average (ECMWF, 2009; KNMI, 2009). Since wind damage to forests generally occurs during events with high wind speeds, we take the maximum observed average hourly wind speed in a year as indicator for the wind climate.

Fires and storms can influence all forest functions and services, like timber production, water and soil protection, biodiversity and landscape amenity. Exposure is defined as the value of all these functions. However, many of these are difficult to quantify. The easiest quantifiable variables are forest area and timber volume. Since forest fires are usually expressed in terms of area affected, we take total forest area as a proxy for exposure to fire risk. Similarly, wind damage is usually reported in terms of wood volume damaged, so we take total growing stock volume as a proxy for exposure to wind damage.

Vulnerability of a forest to fire greatly depends on fuel characteristics: how much fuel is available, how is it distributed and how flammable is it (Fernandes et al. 2000)? Fuel sources are live biomass like foliage, branches, stems, lichens and shrubs and dead biomass like litter and humus. An even horizontal distribution of fuel will facilitate a fast fire spread, both at the stand scale (Agee and Skinner, 2005) as well as on the landscape scale (Fernandes and Botelho, 2003). A continuous presence of easily ignitable fuel in the vertical direction (ladder fuel, like shrubs, dead branches and lichens) greatly contributes to the risk that a ground fire will develop into a crown fire (Agee and Skinner, 2005). Flammability of fuel partly depends on its size: the smaller the fuel, the more easily it is ignited. In general, such conditions are found especially in young stands (Vélez, 1985; Brown and Smith, 2000). With increasing age, tree height and crown base increase and fire risk generally decreases. The chemical composition of the fuel is also important. Generally, coniferous species burn more easily than broadleaved species (Meyer, 2003), with Pinus pinaster, P. halepensis and P. radiata regarded as highly flammable species (Fernandes et al. 2008). Within the broadleaved tree species, sclerophyllous oak forest or coppice (mostly *Quercus ilex* and *Q. suber*) are reported to burn more frequently than could be expected from their share in the forest area (Le Houérou, 1981).

Tree species composition is also important for vulnerability to wind. Coniferous species are considered more vulnerable to wind damage than broadleaved species, with Norway spruce (*Picea abies* (L.) Karst) being regarded as particularly vulnerable (Schütz et al., 2006). Though rooting depth is an important factor in vulnerability to wind, many other factors play a role as well. The tree and stand variables most important with regard to tree stability are tree height and the ratio of tree height to stem diameter at breast height (h/d ratio). Taller trees are more exposed to the wind than shorter ones, for example. Because stand or tree age is highly correlated with tree height, age is often used as a proxy for height. For both wind and fire, age and tree species composition are found to be important indicators of vulnerability. These two can usually be extracted from historic inventory data for a range of European countries, and from model simulations for the future. For the purpose of this study, we developed the following vulnerability indicator:

$$V_i = \sum_j (a_{j,young} \times b_{j,young} + (1 - a_{j,young}) \times b_{j,mature})$$

where V is the vulnerability, i is the type of disturbance (wind or fire), $a_{j,young}$ is the area share (relative to total forest area) of tree species group j below a certain threshold age, $b_{j,young}$ is the relative vulnerability of young stands of tree species group j and $b_{j,mature}$ is the relative vulnerability of mature stands of tree species group j. Table 4.1 gives an overview of the groupings of tree species, relative vulnerability scores and threshold ages used. Threshold ages for fire are averaged from Meyer (2003).

Table 4.1. *Vulnerability scoring of tree species with regard to fire and wind risk.*

Disturbance type (i)	Tree species group (j)	$b_{j,young}$	$b_{j,mature}$	Threshold age
Fire	Broadleaves except Q ilex and Q suber	2	1	50
	Douglas, fir, spruce	3	1	50
	Coppice	2	2	50
	P sylvestris and other pines	4	2	50
	Q ilex and Q suber	6	4	50
	P nigra, P halepensis, P pinaster	6	4	50
Wind	Broadleaves except poplar	1	3	80
	Poplar	1	4	10
	Conifers other than Norway and Sitka spruce	1	4	40
	Norway and Sitka spruce	1	6	40

Threshold ages for wind vulnerability are derived from observed onset of wind damage. These are obtained for broadleaves from Winterhoff et al. (1995), for Norway and Sitka spruce from Schmid-Haas and Bachofen (1991), and for poplar from OBV (2009). For other conifers, the same onset age as spruce is assumed. Relative fire vulnerabilities are a combination of relative insurance premiums in different risk classes of forest fire insurance in the Netherlands (OBV, 2009) and the rating of Meyer (2003). Relative wind vulnerabilities are a combination of relative insurance premiums in different risk classes of windfall insurance in the Netherlands (OBV, 2009) and observed differences in share of damaged area in relation to total forest area after a number of storms (Grayson, 1989; Lüpke and Spellmann, 1997; Jalkanen and Mattila, 2000). The relative vulnerabilities for both fire and wind range from 1 (low vulnerability) to 6 (high vulnerability), and thus also the calculated total vulnerability score can range between 1 and 6**.**

4.3 Data

Historical wind hazard was calculated from the Re-Analysis data at ECMWF (2009), including data for the period 1948-2007. These data include six-hour observations of temperature, wind speed and precipitation, with a spatial resolution of about 250 by 250 km. For each grid cell, the maximum observed wind speed (hourly average) per year was extracted. From this series, also the average maximum annual wind speed was calculated, giving an indication of the severity of the wind climate. Historical fire hazard (FWI) in the months June, July and August was calculated from the Re-Analysis data at the ECMWF, with a resolution of 50 by 50 km, including data for the period 1975-2005. For both wind and fire hazard, a GIS was used to calculate national averages for the time span covered. Historical data on forest fire area and damaged volume by wind were taken from the Database on Forest Disturbances in Europe (Schelhaas et al. 2001), for the same periods as the hazard maps. This dataset was updated by reviewing recent literature and damage reports. Vulnerability scores were calculated from a database containing aggregated information from national forest inventories in Europe (Schelhaas et al., 2006). The reference date of this dataset varies per country, but on average is dated around 1995. Exposure (forest area and growing stock) was derived from MCPFE (MCPFE, 2007).

The maps on vulnerability, exposure and hazard were then compared to the actual damage maps, using linear regression where possible. For a selection of countries, historic evolution of vulnerability, exposure and hazard was studied to see if changes in these drivers can explain observed damage patterns. Historic vulnerability was calculated from historic national inventory reports. For fire, we selected Finland, the United Kingdom, Denmark, Poland and Italy. For wind we selected Finland, the United Kingdom, Denmark and the Czech Republic. No Mediterranean country was included, since data on wind damage for these countries are lacking.

4.4 Results - fire

The hazard, expressed as summer FWI, clearly shows a north-south gradient, with the highest values in the Mediterranean Basin (Figure 4.2). Exposure, expressed as forest area, shows a more differentiated picture (Figure 4.3). A high forest coverage is found in areas where terrain is unsuitable for agriculture (hilly areas, mountain ranges), or where population is scarce. Lowest forest cover (10-15%, MCPFE 2007) is found in industrialised Western European countries like Ireland, United Kingdom, the Netherlands and Denmark. Forest cover is particularly high (40-75%, MCPFE 2007) in Scandinavia, Russia and the Baltic

States. In the Balkan and Mediterranean Basin, forest cover is medium (30-60%, MCPFE 2007), with again a concentration of forest in mountainous areas. The vulnerability of the forest (Figure 4.4) depends mainly on the share of young forest with easily flammable species. The vulnerability is generally low in the Balkan, Alpine and Central European countries, due to the relatively large share of old stands. Countries with large afforestation programmes with conifers, like Denmark, Ireland, the United Kingdom and Poland, show rather high vulnerabilities. Also in the Mediterranean Basin, vulnerability is rather high, through a combination of the use of coppice and the widespread occurrence of flammable species. The majority of fire damage occurs in the Mediterranean Basin, judging from the percentage of the area of forest land that is damaged annually (Figure 4.5). Also the average fire size is considerably larger in the Mediterranean Basin (Figure 4.6).

For a set of 21 countries we have all information on damage, hazard, vulnerability, and exposure. Vulnerability and hazard are significant predictors for damage (expressed as the percentage of area that is burned annually), giving an R^2 of 0.74.

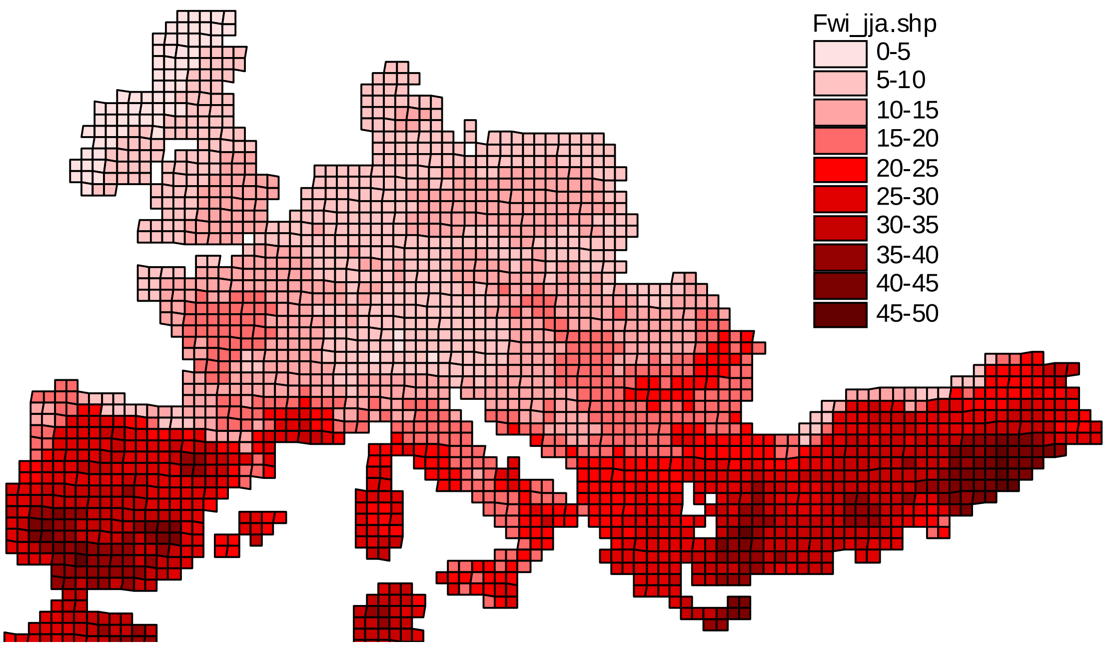


Figure 4.2. *Mean FWI index for the months June, July and August over the period 1975-2005.*

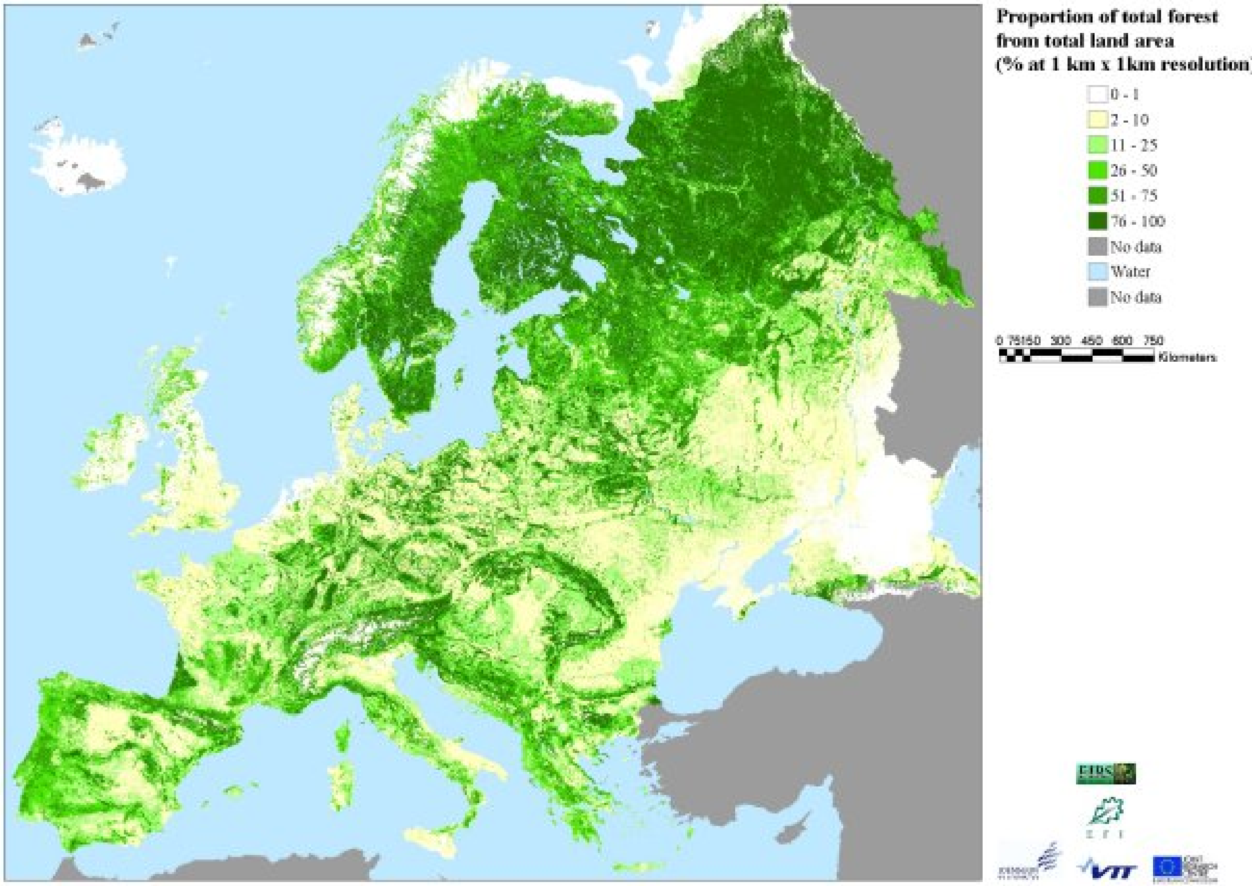


Figure 4.3. *Distribution of forests in Europe, expressed as forest cover percentage per 1 km x 1 km grid cell (source: EFI).*

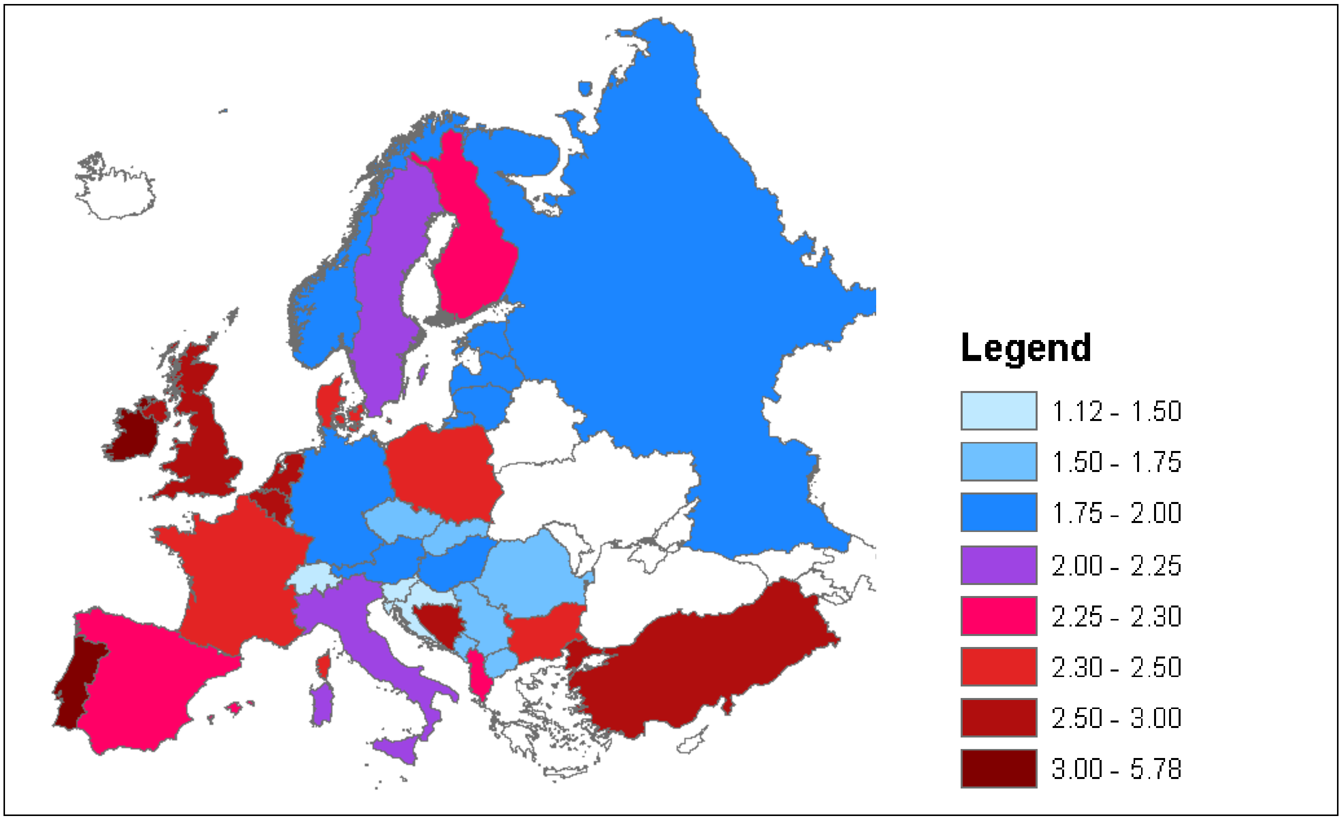


Figure 4.4. *Vulnerability score for forest fire per country (based on data from Schelhaas et al., 2006).*

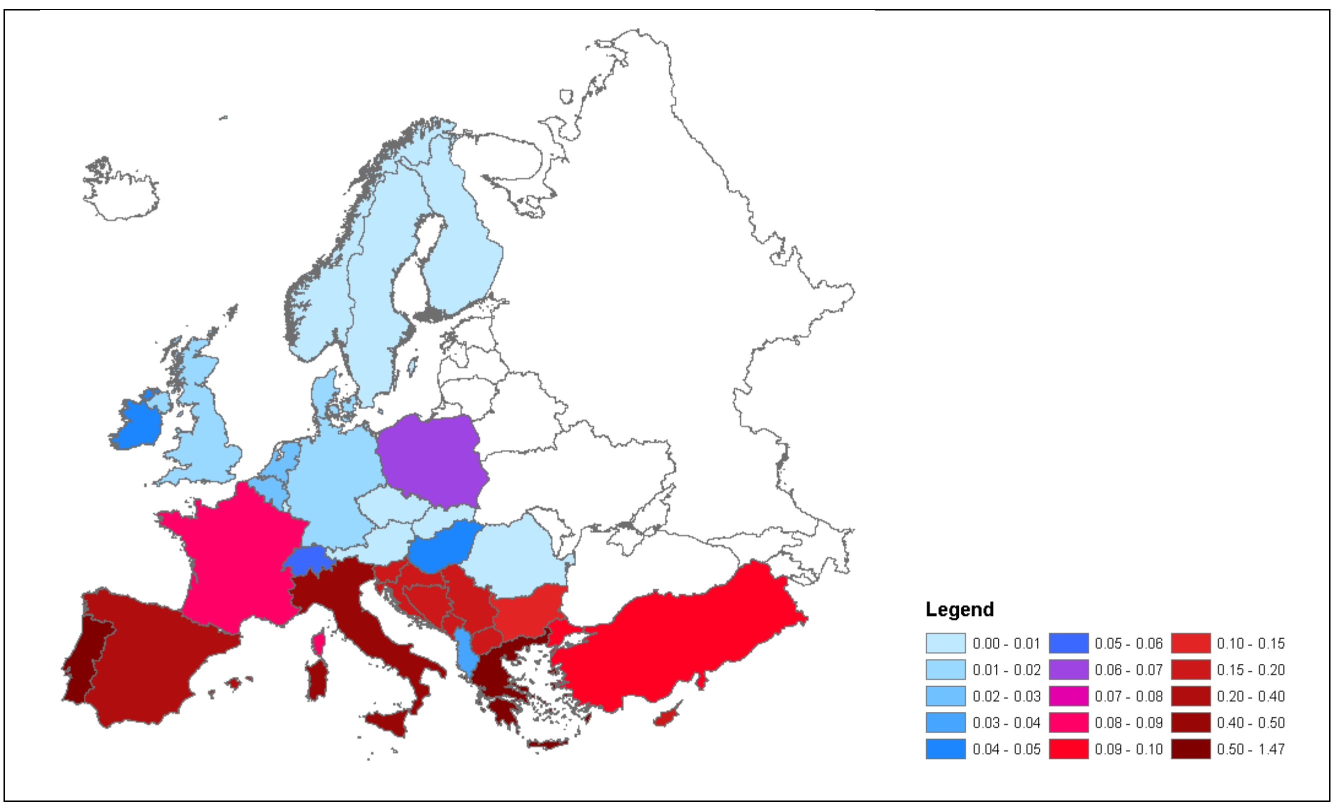


Figure 4.5. *Percentage of area of forest land annually burned (Schelhaas et al., 2001).*

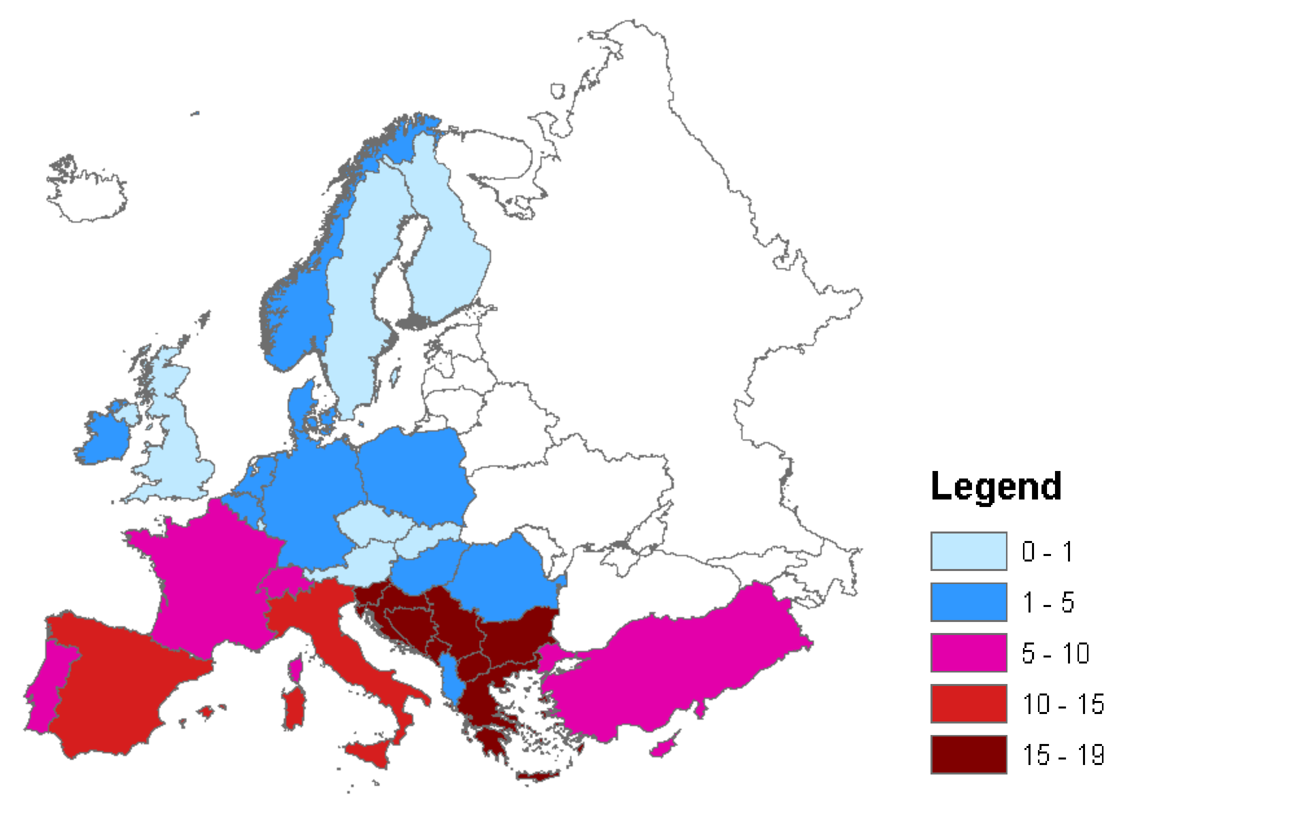


Figure 4.6. *Average fire size per country (Schelhaas et al., 2001).*

In the period 1975-2005, the average FWI in summer for Finland was 1.8, while in Italy it was 15.3 (Table 4.2). The United Kingdom, Denmark and Poland showed intermediate values in the range from 8.5 to 10.0. If we express the annual burned forest area as a percentage of the forest area in 2000, we see more or less the same pattern as in the distribution of the FWI. Annual fire area in Finland is very low (0.00%), in Denmark and the United Kingdom it is 0.02%, in Poland 0.13% and in Italy 0.72%. All countries showed an increase in exposure in the period 1950-2000, and in all countries the forest area is projected to increase further in future. Regarding the vulnerability, different countries showed different patterns. Poland had large afforestations after the Second World War, mainly with conifers, leading to high vulnerabilities around 1950. As these plantations got older, a lower vulnerability resulted in 2000. In Denmark and the United Kingdom the expansion of forest area continued longer, leading to a stable vulnerability between 1950 and 2000. Finland showed an increase in vulnerability between 1950 and 2000, probably due to the regeneration of many old stands and the focus on coniferous species. For Italy, no information on age class structure prior to 1985 was available. Between 1985 and 2000, vulnerability was constant. For each country we interpolated vulnerability and exposure to get continuous time series. In the regressions only FWI came out as significant predictor for fire risk per year.

The Mediterranean Basin suffers most from forest fires, which can be linked to dangerous weather conditions in summer, visible as a high FWI, and to a relatively high vulnerability of the forest. A low average FWI does not guarantee a low risk, since FWI varies from year to year. In extreme years FWI still can reach high values. In combination with a high vulnerability, this might still lead to large fires. The variability in FWI is much higher than changes in exposure or vulnerability, which explains the non-significance of the latter two.

Table 4.2. *Indicator values for fire risk*

	Finland		Denmark		United Kingdom		Poland		Italy	
FWI	1975-2005	1.8	1975-2005	8.5	1975-2005	9.1	1975-2005	10.0	1975-2005	15.3
Vulnerability	1952	2.0	1951	2.3	1980	2.6	1968	2.8	1985	2.1
	2000	2.4	2000	2.3	2000	2.6	2000	2.4	2000	2.1
Exposure (Mha)	1952	17.4	1951	0.37	1950	1.5	1956	7.4	1950	5.6
	2000	20.3	2000	0.49	2000	2.2	2000	8.4	2000	6.4
Fire area (ha/yr)	1975-2006	556	1974-1997	173	1990-2001	495	1990-2005	6780	1975-2002	46688
Fire area (% relative to 2000)	1975-2006	0.00	1974-1997	0.02	1990-2001	0.02	1990-2005	0.13	1975-2002	0.72

We defined vulnerability as an index of the combined age class distribution and the tree species distribution. The major reason for this definition was the large-scale availability of data to calculate this index. However, much more factors play a role in vulnerability, like fuel build-up within the stands, the spatial arrangement of stands, accessibility to the forest, distance to water sources, etc. It is virtually impossible to combine these factors in one vulnerability index, and even then the required data would probably be not available over large areas.

4.5 Results - wind

The maximum annual wind speed that can be expected above land is clearly linked to distance to the Atlantic Ocean and other seas (Figure 4.7). Most of the coastlines experience average maximum wind speeds above 15 m/s. Peak gusts during storms can then reach up to 50-60 m/s. Exposure is expressed as growing stock volume. The average volume per ha is particularly high in Central European countries like Switzerland, Austria, Czech Republic and Germany (Figure 4.8). These countries therefore also have high total growing stock volumes (Figure 4.9). Countries with less growing stock per hectare, but a high forest cover also have considerable growing stock volumes, like for example Sweden, southern Finland and Scotland. The vulnerability of the forest to wind damage (Figure 4.10) depends mainly on the share of old spruce stands. The highest vulnerabilities are found in Central Europe (Switzerland, Austria, Germany, Czech Republic) and in Scandinavia, including the Baltic States. We can express wind damage as the percentage of growing stock that is annually damaged by wind (Figure 4.11). We find that most wind damage occurs in the Atlantic countries and in Central Europe.

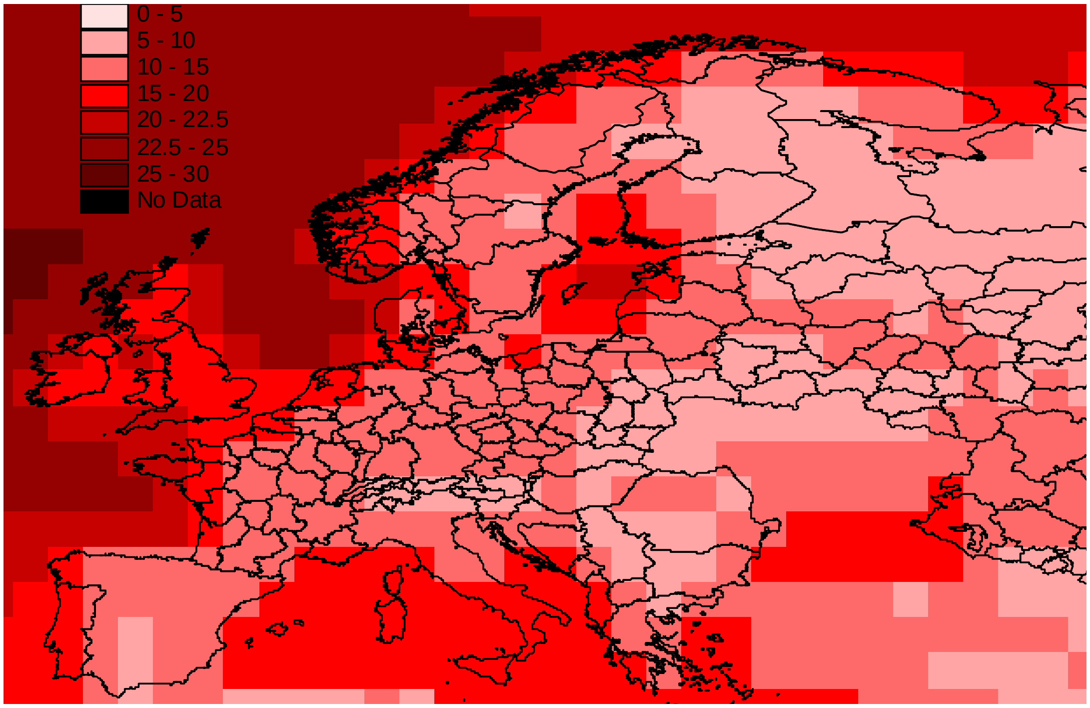


Figure 4.7. *Maximum annual wind speed (in m/s; average per hour), averaged over the period 1948-2007.*

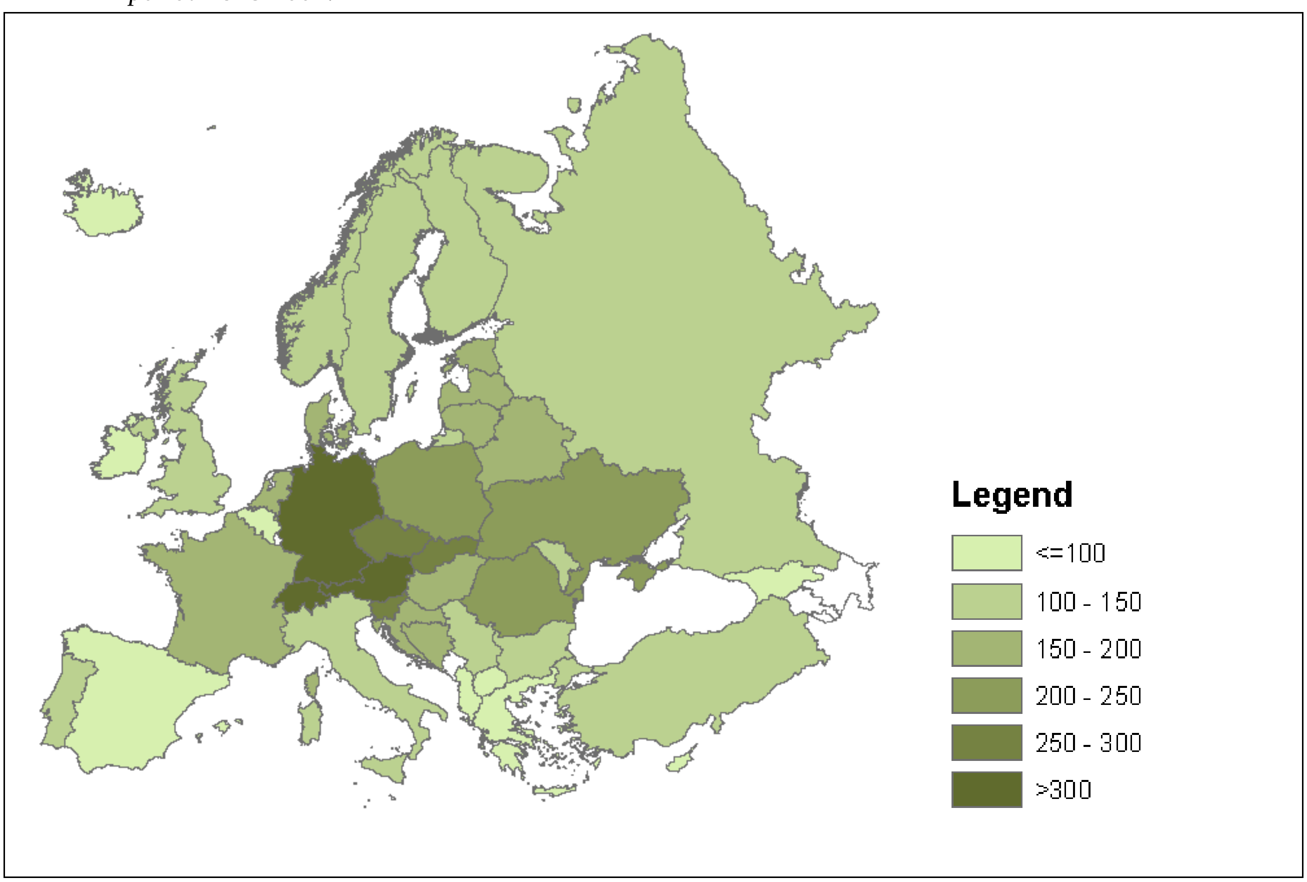


Figure 4.8. *Average standing wood volume per ha in 2005 (MCPFE 2007).*

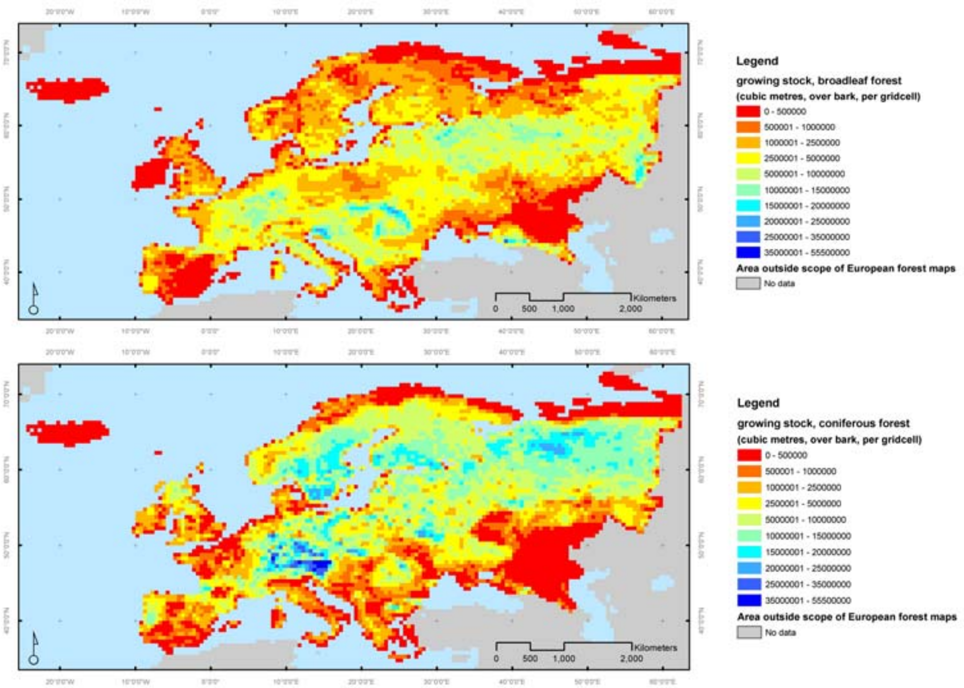


Figure 4.9. *Current standing wood volume for broadleaves (top) and conifers (bottom) (pers. com. Jo van Brusselen, EFI).*

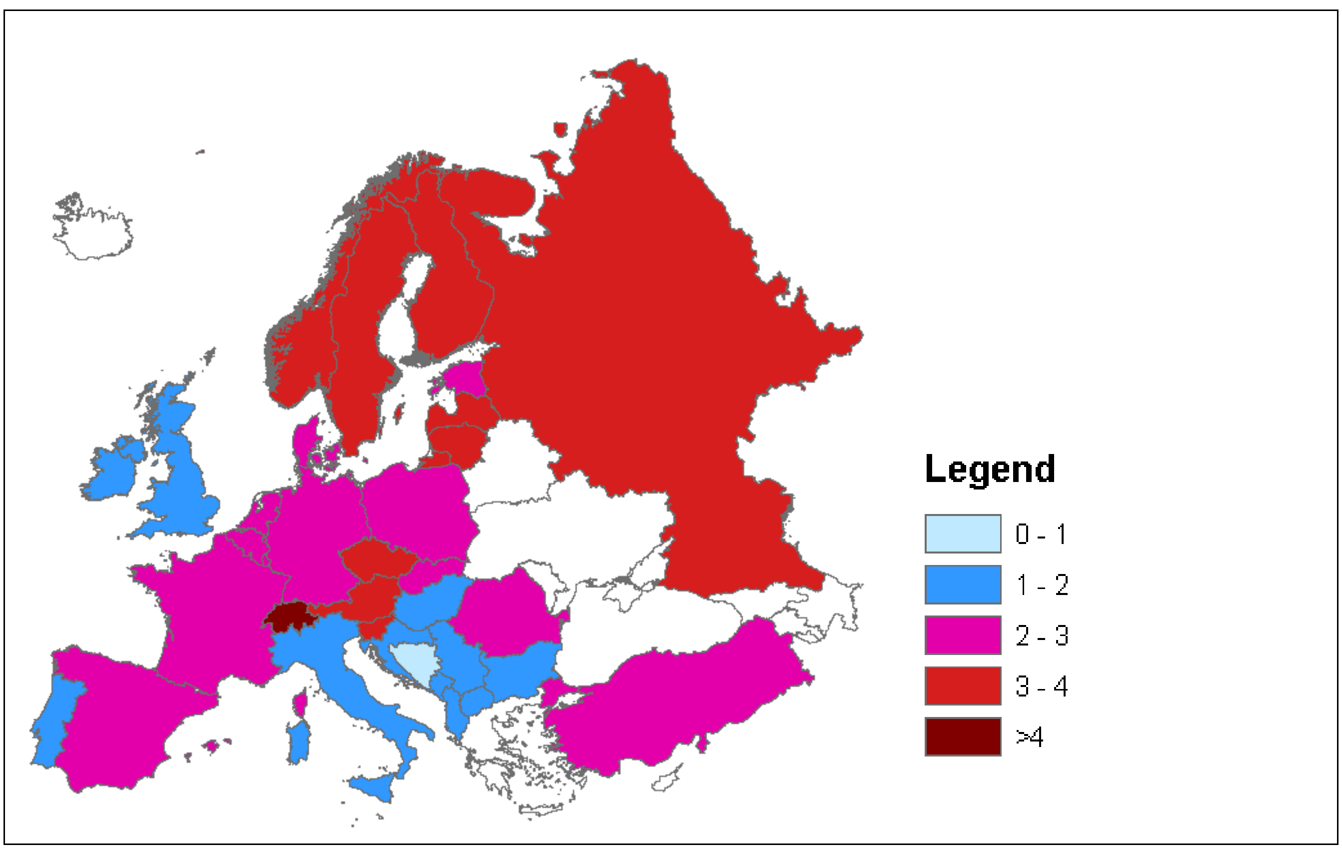


Figure 4.10. *Vulnerability score for wind damage per country (based on data from Schelhaas et al., 2006).*

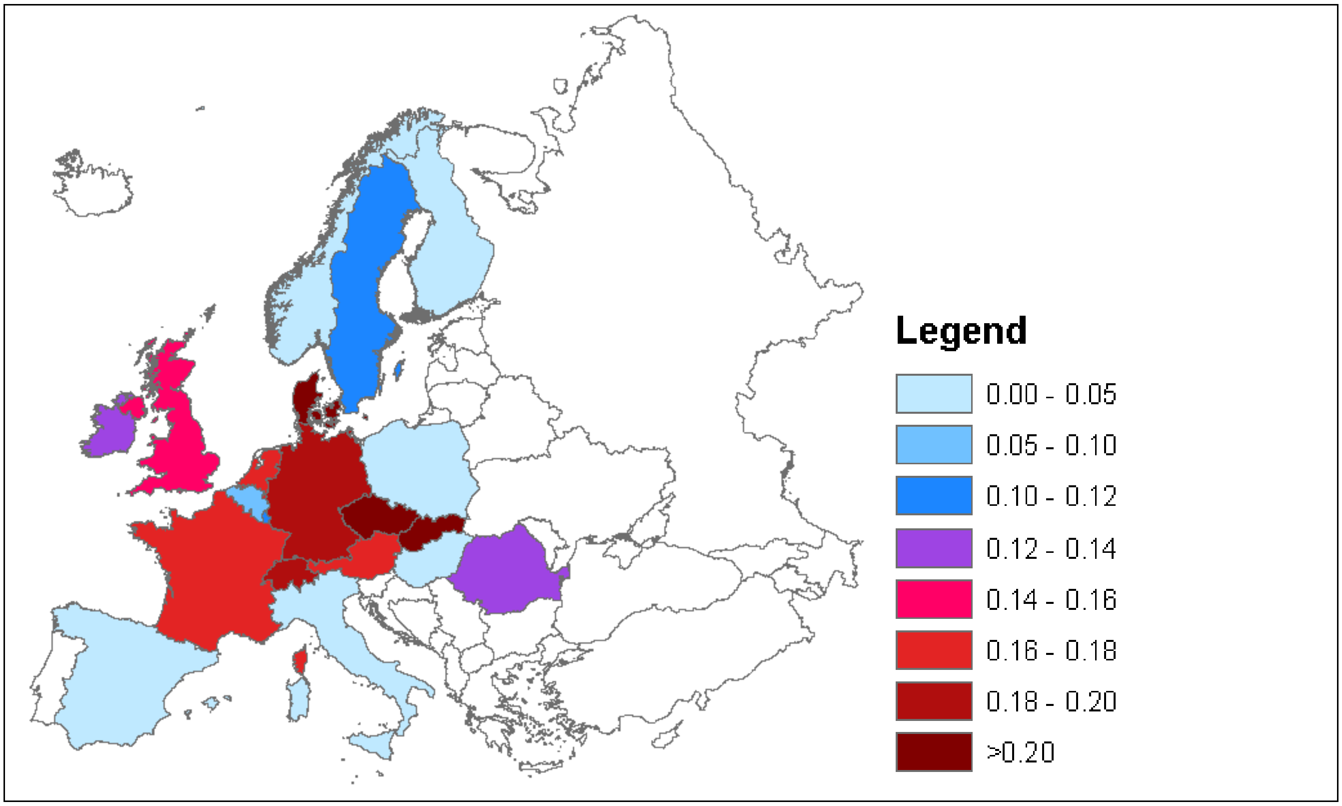


Figure 4.11 *Percentage of the growing stock annually damaged by wind (wind damage data Schelhaas et al., 2001; growing stock data MCPFE 2007).*

The United Kingdom is fully exposed to depressions coming from the Atlantic and on average experiences an annual maximum wind speed of 19.4 m/s (Table 4.3). Denmark is a bit more sheltered with values of 18.1 m/s. In Finland the average annual maximum is 10.4, while in the Czech Republic it is 12.2 m/s. The Czech Republic reported the highest amount of damaged timber in the period 1948-2007 with 107.7 million m^3 (Table 4.3). Damage in the other three ranged from 16.0 in Poland to 19.7 million m^3 in Finland.

Due to its skewed age class distribution, the United Kingdom shows the lowest vulnerability of the countries under study. It increased from 1.6 in 1980 to 1.7 in 2000. Denmark showed a similar development, with little change between 1951 (2.0) and 2000 (2.2). Due to the harvest of older stands in Finland, vulnerability decreased from 3.9 in 1952 to 3.0 in 2000. Vulnerability in Czech Republic was stable over the last half a century at 3.5. Exposure, expressed as the total timber volume in a country, is strongly related to the forest area in a country. Denmark only has little timber volume (74 million m^3 in 2000) in comparison with Finland (over 2 billion m^3 in 2000). All countries showed a huge increase in timber volume over the period 1950-2000. Regressions did not identify clear predictors for wind damage.

***Table 4.3**. Indicator values for wind risk*

	Finland		Denmark		United Kingdom		Czech Republic	
Wind speed	1948-2007	10.4	1948-2007	18.1	1948-2007	19.4	1948-2007	12.2
Vulnerability	1952	3.9	1951	2.0	1980	1.6	1950	3.5
	2000	3.0	2000	2.2	2000	1.7	1994	3.5
Exposure (Mm^3)	1952	1538	1950	39	1950	110	1950	322
	2000	2091	2000	74	2000	267	2000	631
Damage (Mm^3, total in period)	1948-2007	19.7	1948-2007	16.0	1948-2007	17.9	1948-2007	107.7
Damage (total compared to 2000)		0.9		21.5		6.7		17.1

A requirement for wind damage to occur is a sufficiently large wind speed. The relatively high occurrence of damage in the Alpine region (Figure 4.11) is in contrast with the low wind speeds according to Figure 4.6, and with reported wind speeds for damaging events in this region (Schütz et al, 2006). A likely reason is that wind speed data in the Re-Analysis data do not take into account influences of the topography. Smits et al. (2005) also report inconsistencies in these kind of data, which might explain the fact that highest annual wind speed was not a good predictor for wind damage. Better wind speed datasets might give better results, but such high-quality datasets are very rare (Smits et al., 2005).

High vulnerability scores and high exposure seem to be correlated (compare Figure 4.8 and 4.10), which can be explained by the fact that old spruce stands can contain very high standing volumes. Such stands are mainly found in Central Europe. Apparently the storm frequency is not high enough to prevent the occurrence of such stands, but when storms occur they can do a lot of damage. In the Atlantic area, vulnerability is not particularly high, and neither is the growing stock per ha. However, storms occur here frequently and do damage to the forest.

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