POTSDAM-INSTITUT FÜR KLIMAFOLGENFORSCHUNG

Originally published as:

Holsten, A., Kropp, J. P. (2012): An integrated and transferable climate change vulnerability assessment for regional application. - Natural Hazards, 64, 3, 1977-1999

DOI: 10.1007/s11069-012-0147-z

An integrated and transferable climate change vulnerability assessment for regional application

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Abstract

While sectoral vulnerability assessments have become common usage in the climate change field, integrated and transferable approaches are still rare. However, comprehensive knowledge is demanded to concretize and prioritize adaptation strategies, which are currently being drafted at national and state levels. We present a multisectoral analysis where sensitivity is quantified by the physical, social, environmental and economic dimension by means of tailor-made approaches for specific sectors. These are directly related to relevant exposure variables defined as relative climatic changes until the end of this century. Aggregation of the sector-specific impacts, comprising both sensitivity and exposure, leads to integrated impact measures. These are then combined with the generic adaptive capacity. We exemplify our methodology for municipalities in the German state North Rhine-Westphalia for two regional climate models. Our approach allows for the integrated assessment, while at the same time enabling a sector-specific perspective. However, various limitations remain, especially regarding the aggregation across sectors. We emphasize the need to consider the aim and methodological advantages and disadvantages before applying any vulnerability assessment.

Keywords: Impact assessment, Global warming, Extreme event

1 Introduction

Climate change is increasingly recognized as a global challenge, especially regarding its impacts on the natural and human systems (IPCC, 2007). For the development and prioritization of adaptation strategies, decision-makers require comprehensive information on regional vulnerabilities over a wide range of sectors. Spatially explicit vulnerability assessments have become common usage (Preston et al., 2011), especially with a sectoral focus (e.g. Zebisch et al., 2005; O'Brien et al., 2004; Ciscar et al., 2011). However, the operationalization of such approaches is still challenging due to their interdisciplinary character, spatially and temporally heterogenous processes and due to normative judgements involved (Preston et al., 2011; Hinkel, 2011). Therefore, integrated assessments still remain rare, particularly regarding the consideration of both biophysical and socioeconomic determinants. Moreover, existing methodologies are heterogenous and lack transferable methodologies (Preston et al., 2011). Thus, novel ways of comprehensive vulnerability analysis, which integrate sectors or dimensions, are in demand.

We operationalize a climate change vulnerability assessment in a transferable and comparable way by means of tailor-made approaches for various sectors. We exemplify our methodology for the German state North Rhine-Westphalia (NRW). The assessment of its vulnerability is of special interest to decision-makers, which is apparent from previous climate change-related studies financed by the state (Spekat et al., 2006; Kropp et al., 2006, 2009). Based on these results, an adaptation strategy at state level has been published in 2009 (MUNLV, 2009). However, this sectorally-focused strategy is still at an early stage and lacks further concretization and prioritization regarding specific adaptation measures. We therefore aim at a more detailed and spatially explicit knowledge base over a wide range of sectors of this state. This can then support further quantitative assessments regarding regional damage and adaptation costs.

An array of definitions of vulnerability has evolved from different research disciplines such as in the hazard, development and sustainability or climate change context (Fuchs et al., 2011). While the definitions differ between scientific communities, they generally agree on vulnerability being an inner systems condition to experience damages (Birkmann, 2006). We base our work on the common framework within the climate change context following IPCC (2001) and Füssel and Klein (2006): "Vulnerability is the degree to which a system is susceptible to [...] adverse effects of climate change [...] as a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity". The exposure is defined as "the nature and degree to which a system is exposed to significant climatic variations." and sensitivity as "the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli." Sensitivity and exposure lead to impacts as "consequences of climate change on natural and human systems." From these, aggregate impacts can be derived, which express the "total impacts summed up across sectors and/or regions."

Adaptive capacity is "the ability of a system to adjust to climate change [..] to moderate potential damages, to take advantage of opportunities, or to cope with the consequences." Thus, vulnerability V can be regarded as a function of the components adaptive capacity AC and impacts I, which in turn are expressed by the sensitivity S and exposure E:

$$\mathrm{V} = f(\mathrm{I}, \mathrm{AC}), \text{ with } \mathrm{I} = f(\mathrm{E}, \mathrm{S}) \tag{1}$$

Comparing the climate change and the natural hazards community, by and large, the term exposure relates to hazards, sensitivity to vulnerability, adaptive capacity to coping capacity or resilience and the final vulnerability to risk (Costa and Kropp, 2012). Thus, albeit different naming, a general consensus exists in the meaning of the vulnerability components between the different scientific communities. However, vulnerability frameworks still remain abstract and lack an indication regarding their aggregation procedure (Hinkel, 2011). In the following, we therefore propose a formalization of a method to aggregate these components. While arithmetic mean or multiplication algorithms are common in existing climate change-related studies (Hinkel, 2011), Lin and Morefield (2011) propose a "vulnerability cube", which groups vulnerability values by means of axis expressing specific indicators in a multidimensional cube. However, they focus on the visualization with limited options for quantification. Other approaches entail advanced quantitative cluster analysis to develop spatial typologies of vulnerability, which has been carried out for NRW by Kropp et al. (2006). However, this limits the decision-making process because the politically essential identification of dominant components cannot be undertaken. While previous sectoral or integrated studies assessing the consequences of climate change for NRW have neglected the adaptive capacity (Kropp et al., 2006; Lissner et al., 2012; Klaus et al., 2011), we include this key component. Thus, we combine existing approaches to quantify the regional vulnerability and at the same time ensure an interpretation of the results through a transparent aggregation method.

First, we present a standardized framework for a vulnerability analysis and describe its components and aggregation procedure. After introduction to the main characteristics of the study area NRW, we apply this methodology to its municipalities by using the regional climate models CCLM and REMO. Spatially explicit results of impacts and vulnerability are then discussed and main conclusions of our approach are drawn.

2 Methods and data

2.1 Comparable and transferable methodology of a vulnerability analysis

An integral part of any vulnerability analysis is the aggregation methodology of its components. Preston et al. (2011) identify as a key challenge the lack of specificity in existing vulnerability assessments to state which system is vulnerable to which climatic stimuli. Therefore, system specific linkages between sensitvity and exposure variables are essential. In the disaster reduction context, vulnerability is described by the "individual and collective physical, social, economic and environmental conditions" (UN/ISDR, 2004). The physical dimensions refers to the built environment including settlements and infrastructure, the social dimension considers the human wellbeing, the economic dimensions represents economic activities such as agriculture or tourism and the environmental dimension refers to the natural environment. We integrate this into our vulnerability framework as a basis for our analysis, which comprises the components E, S, I and AC as well as the four dimensions (Fig. 1).

While climatic changes are often apparent in the form of extreme events (Rahmstorf and Coumou, 2011; IPCC, 2011), also incremental developments may result in extreme events in terms of natural or societal impacts (Glade et al., 2010). We, therefore apply exposure variables as proxies for extreme events and for slower climatic changes. Thus, identified relevant climatic stimuli are transferred to exposure variables prior to the aggregation to the impacts. To consider the direction of change, absolute exposure variables $\mathrm{E_i}$ are between -1 (decrease in climatic stimuli) and 1 (increase), based on the maximum absolute change in either direction $\mathrm{E_{max}}$ for the whole regional data range. Thus, relative changes in the exposure variables are given by:

$$\mathrm{E_{norm}} = \mathrm{E_i} / \left|\mathrm{E_{max}}\right| \tag{2}$$

For a graphical representation of this procedure, exemplified for changes in heavy precipitation days occurring over municipalities, see Fig. 2.

In contrast to the exposure, sensitivity and adaptive capacity as a dimensionless characteristic of the system are characterized by solely positive values. We focus on the relative vulnerability; therefore sensitivity values (e.g., sensitivity of forests to windthrow within a region) are first multiplied by the local relevance of each indicator prior to the rescaling procedure (e.g., share of forest area within the region).

The following rescaling of sensitivity values $\mathrm{S_j}$ (and analogously adaptive capacity) based on minimum and maximum values within the data range ($\mathrm{S_{min}}$ and $\mathrm{S_{max}}$) is given by $\mathrm{S_{norm}} = (\mathrm{S_j} - \mathrm{S_{min}})/(\mathrm{S_{max}} - \mathrm{S_{min}})$. Thus, rescaled values of sensitivity and adaptive capacity range between 0 (low) to 1 (high). In our approach, we consider adaptive capacity in a generic manner, encompassing various sectors. This includes general factors such as education or income (Adger et al., 2007).

While existing studies have focused on single components of vulnerability separately, few have given their combination a deeper thought (Hinkel, 2011). Two aggregation methods are common in vulnerability assessments: the arithmetic mean of the influencing factors or the multiplication. The latter implies that the inputs are perfectly substitutable, thus allowing for a compensation between them. This has been applied for a cross-

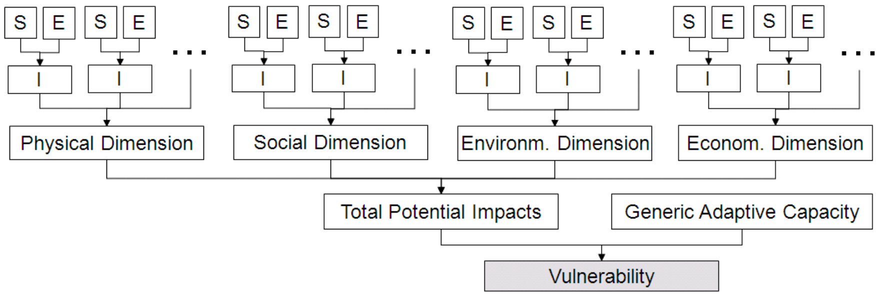

Figure 1: Schematic overview over the components and dimensions of the vulnerability analysis. Sensitivity indicators (S) are combined with relevant exposure indicators (E) expressing specific impacts (I). These are aggregated to the physical, social, environmental and economic dimension and to the total potential impacts. Together with the generic adaptive capacity they describe the vulnerability.

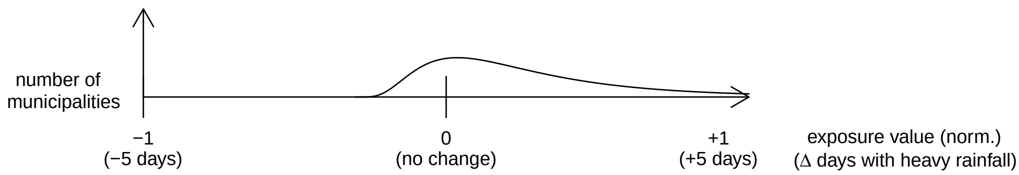

Figure 2: Rescaling procedure of exposure variables: Schematic distribution of climatic changes over the municipalities, exemplary for changes in heavy precipitation days. Changes are displayed by their absolute value and their values after rescaling.

sectoral analysis of climate change impacts in Germany (Rannow et al., 2010). However, regarding the calculation of climate change-related impacts from exposure and sensitivity, an aggregation algorithm seems suitable, which ensures that no climatic changes (i.e. zero exposure) always lead to zero impacts. This is visualized in Fig. 3, where zero impacts are represented in gray color according to an algorithm based on the arithmetic mean or multiplication.

We therefore quantify the impacts within a dimension (physical, social, environmental or economic), e.g., I_{phys}, based on the rescaled sensitivity ($S_{norm,k}$) and exposure values ($E_{norm,k}$) for all specific impacts within a dimension (with a maximum number of n):

$$\text{e.g. } I_{phys} = 1/n * \sum_{k=1}^{k=n} S_{norm,k} * E_{norm,k} \qquad (3)$$

Thus, the aggregation is carried out according to system-specific relationships between the exposure entity and the climatic stimuli (see also Fig. 1).

Aggregation via an arithmetic mean is often applied in vulnerability studies involving normative arguments (Hinkel, 2011). We apply this algorithm when aggregating the impacts of the four dimensions, e.g. I_{phys} to the total impacts I_{total}. Thereby, weighting factors for the specific dimensions (a to d) can be applied:

$$I_{total} = (a * I_{phys} + b * I_{soc} + c * I_{env} + d * I_{econ})/4 \qquad (4)$$

Even by including specific impacts with a clear direction according to Fig. 3 (right), the subsequent aggregation represents a limitation as it allows for a compensation of impacts across sectors. Yet, we follow this approach to achieve a quantitative aggregation across sectors. It has to be noted that the prior to the aggregation to the four dimensions and the total impacts, a rescaling procedure of the sector-specific or dimension-specific impact values is omitted. Thus, the magnitude of the different impacts is maintained. Only at the final stage, the resulting total impacts are again rescaled to the data space of the NRW and then range from -1 (adverse effects) to 1 (beneficial effects). The consideration of beneficial effects of climate change, which are derived by a diminishing in exposure, is based on the assumption that impact processes between exposure and sensitivity work equally in both ways. Thus, we assume that increases in heavy rainfall days lead to adverse effects (e.g., flooding), while a reduction in these days of the same amount will attenuate the impacts equally.

Experience from vulnerability analysis has revealed a higher relevance of the impacts than the adaptive capacity to local stakeholders, as they could better estimate the latter on their own (Hinkel, 2011). Also, it is still an under-researched topic (Engle, 2011) and little is known on the relationship between climate impacts and adaptive capacity. We therefore refrain from an the aggregation of adaptive capacity as applied for the exposure and sensitivity based on their multiplication. Instead we introduce an visual combination of the calculated values of impacts I and adaptive capacities AC for each municipality to express the vulnerability V (see Eq. 1). Based on Metzger and Schröter (2006) we display the impact by hue and the adaptive capacity value by the transparency of the respective color. Since adaptive capacity can potentially act in both ways, either reducing adverse or increasing positive effects, the transparency increases for adverse impacts from low to high adaptive capacity values and vice versa for

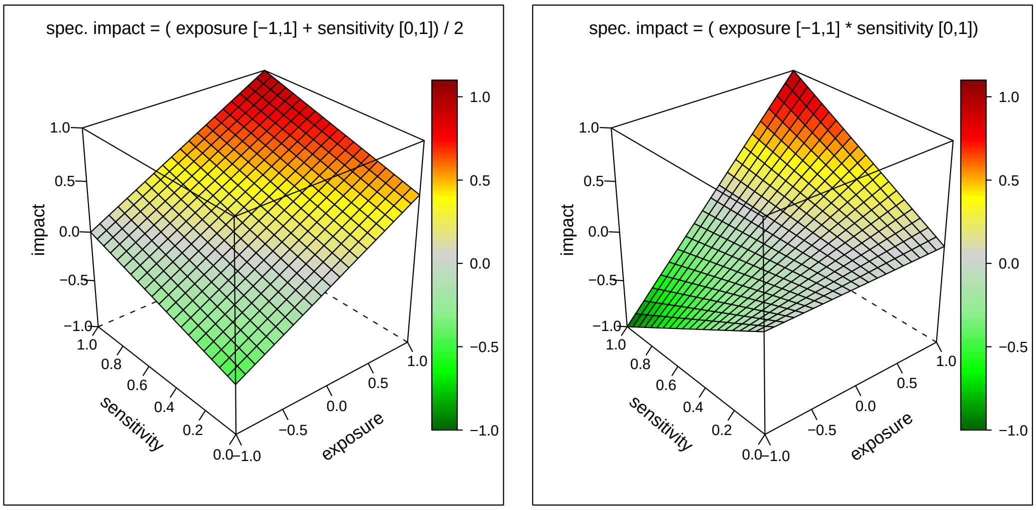

Figure 3: Schematic quantification of specific impacts as a function of exposure [-1 to +1] and sensitivity [0 to 1] based on the arithmetic mean (left) or multiplication (right). Resulting impacts values represent adverse (red) or beneficial effects (green). The multiplication process also entails overall lower absolute impact values. Also, the weighting of the input factors is not homogeneously distributed over the value range as with the arithmetic mean, rather, lower values have a higher influence on the final product.

positive impacts. This way, the different components are still distinguishable and of higher relevance for decision-makers. Given the local knowledge regarding adaptive capacity from stakeholders within their own municipality, this component is more relevant to decision-makers from the broader perspective. Thus, for a wider region, the potential to decrease vulnerability by increasing the local adaptive capacity can be identified.

The various steps of data rescaling lead to relative values of vulnerability. In other words, no absolute statements concerning the final vulnerability (e.g., municipality X is vulnerable) are possible. However, relative statements for the study area can be made, (e.g., municipality X has a much higher vulnerability than municipality Y).

2.2 Application of vulnerability analysis to North Rhine-Westphalia

In the following, we apply the developed concept of a vulnerability analysis to NRW, comprising 396 municipalities (Fig. 4). With a population of 18 million, NRW is the most populous and at the same time the most densely populated state. Regional characteristics are quite diverse in terms of climate, geomorphology and socio-economic structure. Two main types of landscapes can be found, namely the North German Lowlands with elevations just a few meters above sea level and one of the largest metropolitan areas and the North German Low Mountain Range (Sauerland, Eifel Mountains) with elevations of up to 850 m and a lower population density. These main landscapes are also distinguishable by their climatic characteristics: Annual mean temperature amounts to 10°C (1961-1990) in the lowlands and 5°C in the mountain regions. Yearly mean precipitation sums of up to 1500 mm has been recorded in higher elevations, while the Rhine Valley receives 620 mm per year (Kropp et al., 2009). NRW contributes with over 20% to the German GDP (MWEBWV, 2010), thus possible adverse impacts of climate change may have severe consequences in reducing the overall economic performance of Germany.

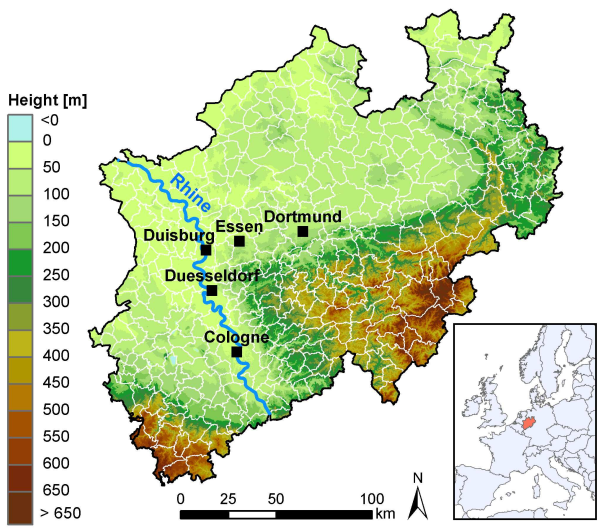

Figure 4: The study area North Rhine-Westphalia. The hatched area indicates the metropolitan Rhine-Rhur region. Municipalities are delineated by white borders.

We selected the impacts based on their climate dependency, regional relevance, data availability and existence of methods or potential for developing new methods of quantification. The vulnerability-creating processes and the relevant indicators are summarized in Tab. 1 (for more details see supplementary material). We aimed at integrating climate-dependent impacts systematically and at the same time consider the largest range of sectors possible. However, for several impacts, sufficient data or suitable methods for quantification were lacking. For example, the energy sector is influenced by climate regarding supply (Förster and Lilliestam, 2009) and demand (Olonscheck et al., 2011) and is of strong economic importance for NRW. However, due to a lack of a coherent database regarding this sector, its water use and other plant characteristics, we could not consider it in our analysis. Climate change is also expected to increase river flooding, especially along the Rhine (Te Linde et al., 2011). Yet, simulations of extreme flooding events involve considerable uncertainties regarding large time horizons. We therefore refrained from including this impact in our analysis. In total, we restricted our analysis to 10 different impacts, which leads to some subjectivity regarding the final results. However, our approach is more focused on demonstrating an integration of different sectoral impacts. Given a larger set of impact processes, the methodology could be applied in the same manner.

Heterogenous scales pose a challenge to vulnerability assessments (Preston et al., 2011; Fekete et al., 2010). According to the concept of scales proposed by Fekete et al. (2010), we focus our analysis on the unit of administrative boundaries and the scale of municipalities (LAU2[1], see Fig. 4), as these are generally in the scope of decision-making processes. They can be scaled up to larger administrative boundaries while being spatially resolved to delineate geographic characteristics of the area. For individual indicators the analysis is based on even more fine-scaled approaches, which are then aggregated to the administrative level.

[1]Local administrative unit according to the Nomenclature of Territorial Units for Statistics of the European Union

Table 1: Overview of sensitivities and relevant climatic stimuli considered regarding the physical (P), social (S), environmental (E) and economic (E) dimension. Positive relationships are marked by ↑ (e.g., impacts on humans increase with increasing heat days), negative feedback processes by ↓. For abbreviations see Tab.2. For more information see annex.

dim.	**exp. unit**	**stimuli**	**regional relevance and relation to exposure**	**method of the sensitivity indicators**
P	settlements	flash floods (CHR ↑)	Settlements within steep river catchments and short time lag of the runoff are prone to flash floods, caused by heavy precipitation (Castro et al., 2008; Collier, 2007). Ca. 20 % of flash floods in Germany occurred within NRW in the last decades, which in relation to its area lies above the average for Germany, with a spatial concentration in the Rhine valley. We therefore quantify the exposure to flash floods by CHR.	We quantify the sensitivity to flash floods by the flow accumulation of runoff water on urban areas due to terrain, land use and soil characteristics.
	settlements	pluvial flooding (CHR ↑)	Also landscape sinks, where water accumulates are threatened (Castro et al., 2008; Grünewald et al., 2009) mainly by drainage problems causing economic damages (Jonkman, 2005). This plays an important role in NRW due to its large sealed area (Held, 2000). Further, NRW comprises sinks or depressions due to former lignite mining often without drainage systems (Drecker et al., 1995; Hydrotec, 2004; Grünewald et al., 2009).In accordance with the previous indicator, we quantify the exposure to pluvial flooding by CHR.	We express the sensitivity to pluvial flooding by the potential of urban areas within landscape sinks to be flooded in cases of heavy precipitation events. This is determined by the potential runoff of the drainage area in relation of the volume of the sink.
S	humans	heat (CHD ↑)	Extremely high temperatures are associated with increased mortality and morbidity rates especially in older age groups (Kosatsky, 2005), which was apparent in NRW during the extraordinary warm year of 2003 (Hellmeier et al., 2007). We therefore represent the exposure by CHD.	A combination of factors, such as heat accumulation in urban areas and social susceptibility regarding the share of elderly population can describe the sensitivity to heat. We, therefore apply the sensitivity indicator developed by (Lissner et al., 2012).
E	protected areas	drought (CWB ↓)	Protected areas experience large impacts in form of distribution changes of species (Pompe et al., 2008), phenological changes (Rybski et al., 2011) or species extinction (Thuiller et al., 2005). In Europe, the Natura 2000 network is of major importance for the conservation aims. Until 2080 over 60 % of the species listed in the Habitats directive could be driven out of the protected areas due to climate change (Araújo et al., 2011). The climatic water balance is a key driver of the distribution of species (Crimmins et al., 2011; Vohland and Cramer, 2009; Svenning and Skov, 2006)	We quantify the sensitivity of these areas by means of existing indicators developed for German habitats of Natura 2000 areas, extended by information on the share species especially sensitive to warmer and drier conditions.
	soils	water erosion (CHR ↑)	Water erosion is especially relevant on temporarily uncovered agricultural soils, representing ca. 32 % of the area in NRW. Considerable damages have already occurred (Kehl et al., 2005), which could be further aggravated by changes in seasonal precipitation patterns (Sauerborn et al., 1999). Soil water erosion is especially high during heavy rainfall events (Müller, 2003; Boardman, 2006), we therefore apply CHR.	The slope and erodibility of the soil describe its sensitivity according to the Universal Soil Loss Equation (Schwertmann et al., 1990; Renard et al., 1997).
	lakes	decrease in water volume (CWB ↓)	Lakes provide numerous services; their water-level regime and lake level fluctuations are of key importance to their structure and functioning (Riis and Hawes, 2002; Coops et al., 2003). Extreme fluctuations might exceed species adaptive capacity (Coops et al., 2003; Leira and Cantonati, 2008), driven by an imbalance in gains and losses of water. We therefore express the exposure by CWB.	Shallow lakes are especially sensitive to a decrease in water volume (Scheffer and van Nes, 2007). We thus relate the exposure to the lakes shallowness, expressed by its surface and volume.
E	winter tourism	shortening of season (CSC ↓)	NRW comprises one of the largest winter sport region north of the Alps, which is of high regional economic relevance with a gross annual turnover in the Sauerland area of around 100 mio € (IFT, 2008). Over 250 snow machines provide conditions for alpine tourism in NRW (WSA, 2011). We therefore quantify the exposure by CSC.	We express the sensitivity of the municipality by the extent of the wintersport infrastructure.
	forestry	windthrow (CSD ↑)	Storms are among the most important natural stressors for forests (Fischer 2003). In 2007, the storm "Kyrill" caused the highest insured losses in Central Europe since at least 1990 (Munich Re, 2008). A third of the European and half of the German forest loss was recorded in NRW (MUNLV, 2010). Exposure is represented by CSD.	We apply sensitivity results from Klaus et al. (2011) of a regression model based on observed damages of the "Kyrill" event in NRW, comprising forest and soil characteristics and topography.
	forestry	forest fires (CRH ↓)	Forest fire occurrence is relatively low in NRW. However, small fire events have occurred each year in the past. During extremely hot summers, fire damage increased considerably. Forest fires in NRW show a stronger correlation with relative humidity than with temperature or precipitation (Holsten et al., 2012), we therefore apply CRH.	We relate changes in humidity to the sensitivity of forest stands, defined soil characteristics, forest composition and distance to settlements.
	agriculture	drought (CWB ↓)	Ca. half of the area of NRW is used for agriculture, two thirds of this area underlies crop production (LWK NRW, 2008) and is highly dependent on climatic conditions. In East Germany, future water deficit is expected to increase leading to droughts and production limitations (Schindler et al., 2007). We therefore express the exposure by CWB.	We express the sensitivity by the water retention capacity of the agricultural soils.

For our analysis we consider two regional dynamical climate models: CCLM and REMO. The relevant exposure variables identified for the impact processes in NRW (see Tab. 1 and 2) are rescaled based on equation 2. However, in order to compare results between the two climate models, the rescaling is carried for the data space of NRW encompassing values for both models ($E_{i,\ CCLM}$ and $E_{i,\ REMO}$):

$$\begin{aligned} E_{norm} &= E_i / |E_{max}| \\ \text{with } E_{max} &:= \max\{|E_{i,\ CCLM}|, |E_{i,\ REMO}|\} \end{aligned} \tag{5}$$

Sensitivity values are calculated according to the methodology summarized in Tab. 1. For quantifying these sensitivities, existing methods were applied where possible, for other sensitivity indicators, we developed new approaches. We focus on the relative vulnerability, therefore sensitivity values (e.g., sensitivity of forests to windthrow within a region) are first multiplied by the local relevance of each indicator (e.g., share of forest area within the region) prior to the rescaling procedure.

The aggregation of the impacts according to equation 4 implies weighting factors for the dimensions. These depend on the regional relevance of the dimensions, which can be obtained from the participation of stakeholders. Due to a lack of such regional knowledge, we apply equal weights. For comparison of the influence of possible unequal weighting factors on the results of the total impacts, we further introduce weighting factors identified for the European perspective by Greiving et al. (2011) from a Delphi-based survey. We rescaled the factors to exclude the cultural dimension, which they have additionally considered, and extract the following weighting factors: physical 0.21, social 0.18, environmental 0.34 and economic 0.27.

Adaptive capacity is strongly dependent on the spatial scale (Adger and Vincent, 2005). Various studies have attempted to quantify adaptive capacity at the national or county level (e.g. Brooks et al., 2005; Cutter and Burton, 2010). We apply generic macro-scale indicators according to the framework of Metzger and Schröter (2006) for European regions to NRW. This means that the resulting generic index captures a cross-sectoral capacity of a region to adapt instead of reflecting the individuals ability. It therefore describes the context within which individual could adapt. Municipalities in NRW are of comparatively small extent, often comprising only one small- to medium-sized city. Therefore, indicator values that are spatially homogeneous at this scale (e.g., implementation level of national or state adaptation strategies) or indicators with underlying processes acting beyond municipalities (e.g., technological resource availability or traffic infrastructure) are not suitable here. We therefore concentrate on economic resources as well as knowledge and awareness (see Tab. 3 and supplementary material for more details). Adaptive capacity values are rescaled analogously to the sensitivity. Due to a lack of projected data of sensitivity and adaptive capacity values until 2100, they are expressed by their current status.

Table 3: Summary of adaptive capacity Indicators. For more details see supplementary material.

Economic resources	Private households	Available income of private households
	Municipality	Status of financial budget of municipality
Knowledge and awareness	Participation	Participation in climate change and sustainability initiatives on municipal level
	Education	% of population with highest education level

2.3 Data

We derived the climate data from the regional dynamical climate models, REMO (Jacob et al., 2006), a hydrostatic model, and CCLM (model version 2.4.11), a non-hydrostatic model (Lautenschlager et al., 2009) with a spatial resolution of 0.1° and 0.2°, respectively. We averaged all available runs covering the period from 1960 to 2100 under scenario A1B (Nakicenovic et al., 2000). According to these models, temperature over NRW will increase by 3-3.3°C and rainfall by 1.6% until 2071-2100 compared to 1961-1990 (Meinke et al., 2010). We calculated absolute changes between these periods for the climatic variables listed in Tab. 2. The applied biophysical and socioeconomic data sources are summarized in Tab. 4. We prepared the data using the softwares Climate Data Operators (CDO), ArcGIS and R (R Development Core Team, 2009).

3 Results

The relative exposure differs strongly between the regions in NRW with strongest increases in heat days in the Rhine valley (Fig 5). Under both models, the mountainous areas exhibit the largest increases in storm days and the strongest reduction in snow conditions, however with different magnitudes of change. Both models deviate considerably in the projection of hydrologic variables, both in the magnitude of change and in the direction. For example, according to the REMO model, the Western region of Sauerland experiences wetter conditions in future, whereas CCLM projects drier conditions.

The spatial pattern of the sensitivity values shows great variations across the sectors (Fig 6). While silvicultural sensitivities are highest in the mountains, the sensitivity toward heat is most severe in the metropolitan area. Regarding the urban flooding processes, regional concentrations of high values are discernable in the Rhine valley as well as at the foothills of the mountains. Strongest susceptibility to erosion is found at the foothills of the Egge mountains in the East, highest sensitivity regarding the agriculture in the lower lying Münsterland. Most sensitive protected areas and lakes are spatially scattered due to their sparse occurrence. The municipality of Winterberg clearly stands out with as the most sensitive regarding winter tourism.

The physical impacts are strongest in the foothills of

Table 2: Value ranges of projected changes in the selected climatic variables and corresponding rescaled exposure values

Abbr.	Name	Abs. range	Norm. range
CWB	Change in climatic water balance [mm] (precipitation - evaporation)	-82.4 - 12.4 -69.7 - 48.6	-1 - 0.15 -0.85 - 0.59
CHD	Change in heat days with daily maximum temperature ≥ 30°C) [# days]	6.2 - 25.0 5.5 - 16.2	0.25 - 1 0.22 - 0.65
CHP	Change in heavy precipitation days with daily precipitation ≥ $20mm$ [# days]	0.2 - 2.2 -1.3 - 4.2	0.06 - 0.52 -0.31 - 1
CHR	Change in relative humidity [%]	-1.7 - -0.5 -1.3 - 0.3	-1 - 0.26 -0.77 - 0.19
CSC	Change in snow cover days [# days]	-16.7 - -1.8 -52.0 - -22.2	-0.32 - -0.03 -1 - -0.43
CSD	Change in storm days with daily maximum wind speed ≥ $20.5ms^{-1}$ [# days]	3.4 - 6.9 0.14 - 5.6	0.49 - 1 0.02 - 0.66

Table 4: Summary of biophysical and socioeconomic data sources

Description	Source
Lake characteristics, elevation (DEM, 50m resolution) and regional characteristics of habitat composition of Natura 2000 sites	Agency for Nature, Environment and Consumer Protection NRW (LANUV)
Regional soil map (BK50, 1:50,000)	Geological Survey NRW
Landuse data, highly reolved (ATKIS25, Authoritative Topographic-Cartographic Information System, 1:25,000), converted to the same resolution as the DEM	State Office for Ecology, Soil and Forestry NRW (LöBF)
CORINE Land Cover data (CLC 2006)	Federal Environment Agency, DLR-DFD 2009
Population density, education, income level, sealed surface on municipal level	Statistical Agency NRW
Information on Special Areas of Conservation	EU Natura 2000 database
Damaged forest area during the storm event "Kyrill" in 2007	State Office for Forest and Timber NRW, see also Klaus et al. (2011)
Forest fire statistics (1993-2009)	Federal Agency for Agriculture and Food (BLE)
Length of ski runs for Sauerland and Eifel mountiains	Roth et al. (2001) and websites of the municipalities
Status of financial budget of municipalities	Ministry of Home and Municipal Affairs NRW (MIK)
Municipal initiatives regarding climate change or sustainability	Energy Agency NRW (Energy Agency NRW, 2009), Agenda 21 Forum (Agenda 21 Forum, 2005), Environmental Ministry NRW (MUNLV)

the mountains and in the Rhine valley for both models (Fig. 7, for maps on the sector-specific impacts see supplementary material). Climate change may have positive impacts in parts of the Rhine valley according to the model REMO, projecting a reduction in heavy rainfall days, which influences the impacts with regard to flash floods and pluvial flooding. Social impacts are in general higher, especially in the metropolitan area within the Rhine valley (see Fig. 4), which is strongly affected by an increase in heat days regarding both climate models. Here, population density and sealed surface lead to local heat islands, thus increasing the impacts. Environmental impacts exhibit lower values than the other dimensions over large parts of the state. This can be partly explained by the low relative sensitivity of the habitats within the protected areas and the lakes, mainly due to the small share of area of these entities within the municipalities. While a large spatial differentiation is apparent for the sensitivity of soils to erosion, areas with strong increases in heavy precipitation events do not overlap areas of high sensitivity. Thus, the impact with regard to soil erosion is diminished. Economic impacts are characterized by a rather heterogeneous picture regarding the sectoral impacts. For forestry, strong impacts are prevalent in the mountains. These comprise both a large share of forest in the municipalities and a dominance of needle-leaved trees, which are especially sensitive to windthrow and forest fires. While storms are projected to increase most in these mountains for both models, changes in relative humidity differ between the models, ranging from general decreases for CCLM to slight increases in the eastern Sauerland mountains for REMO. Therefore, in areas of strong sensitivity to forest fire, potential impacts are alleviated by generally wetter conditions under the model REMO. However, regarding the windthrow, high sensitivity values in the mountains coincide with strong increases in storms, which exacerbates the potential impact. Agriculture shows the strongest relative impacts in the eastern Westphalian Bay with larger agricultural areas and soils of a lower water retention capacity. While only small changes in the climatic water balance occur over this region under the CCLM model, REMO simulates stronger decreases. Winter tourism is most affected in the higher elevated areas of Sauerland with the strongest dependency on this sector. Most intense changes in snow cover are projected for the REMO model, compared to CCLM.

The total relative impacts (aggregated over the four dimensions) range from no changes to adverse effects of climate change over the state for both models (Fig. 8). These are strongest for the upper Rhine valley, especially in the densely populated metropolitan area. Also, the foothills of the mountains exhibit strong impacts, especially the western part of the Sauerland and northern

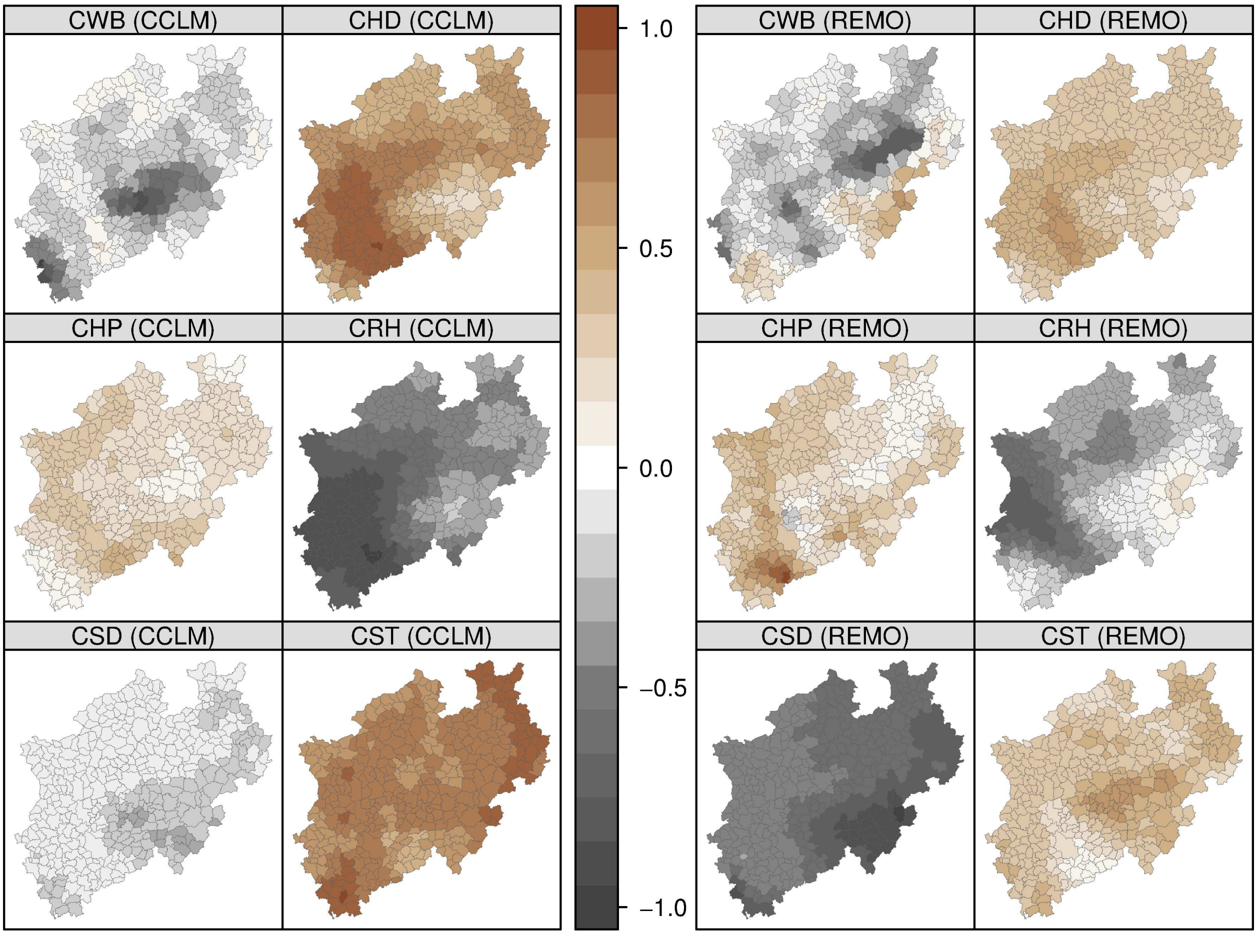

Figure 5: Rescaled exposure variables for the models CCLM (left) and REMO (right). Values are scaled to the data space of NRW for both models, ranging from -1 (decreases) to 1 (increases). The exposure is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B. For abbreviations see Tab. 2

part of the Eifel mountains. As a third affected region, the municipalities in the East of NRW stand out with higher potential impacts regarding the physical and social dimension as well as regarding the forestry sector. Despite the differences in the projected climate data for both models, the total impacts are similar in their spatial pattern. Overall, clearly the social impacts stand out. On the one hand, this is due to a spatial overlap of high sensitivity and exposure values. On the other hand, it is also due to the aggregation methodology, where heat wave impacts are the single determinant indicator for the social dimension, whereas other dimension encompass more impacts. For example, the aggregation of impacts within the economic dimension leads to a lowering of the value for the municipality of Winterberg, with a very high potential negative consequences regarding winter tourism, but beneficial impacts for the agricultural sector under the REMO model.

The application of unequal weighting factors for the four dimensions according to Greiving et al. (2011) results in a very similar spatial distribution of the total impacts (see supplementary material). Comparing the distribution of the total impacts values over the municipalities regarding equal and unequal weights, an decrease in very high values and an increase in lower impacts values can bee seen. This is mainly due to the lower weight of the social dimension, with the overall highest impacts values.

The aggregated impacts have been further overlayed by the generic adaptive capacity, which is displayed using a specific color code. According to both models applied, the overall relative vulnerability to climate change, comprising the total impacts and the generic adaptive capacity, is low for large parts of the lowlands (Fig. 9). By and large, most vulnerable municipalities lie within the metropolitan area, the mountainous areas as well as their foothills, similar to the spatial distribution of the impacts. However, the pattern of vulnerability is more heterogeneous, which is caused by the spatially strongly distributed values of the adaptive capacity. This effect is most apparent in the densely populated metropolitan area, where municipalities display overall high impacts under both models. However, our results show a strong adaptive capacity for several of its municipalities (e.g., Bonn or Düsseldorf), while others are characterized by very low capacities (e.g., Duisburg), mainly due to a strained financial situation. By including the adaptive capacity, climate change effects can be alleviated, resulting in lower values of the vulnerability. This is the case for parts of the Rhine area, while high adverse impacts combined with a low adaptive capacity result in still high vulnerabilities in the Ruhr area.

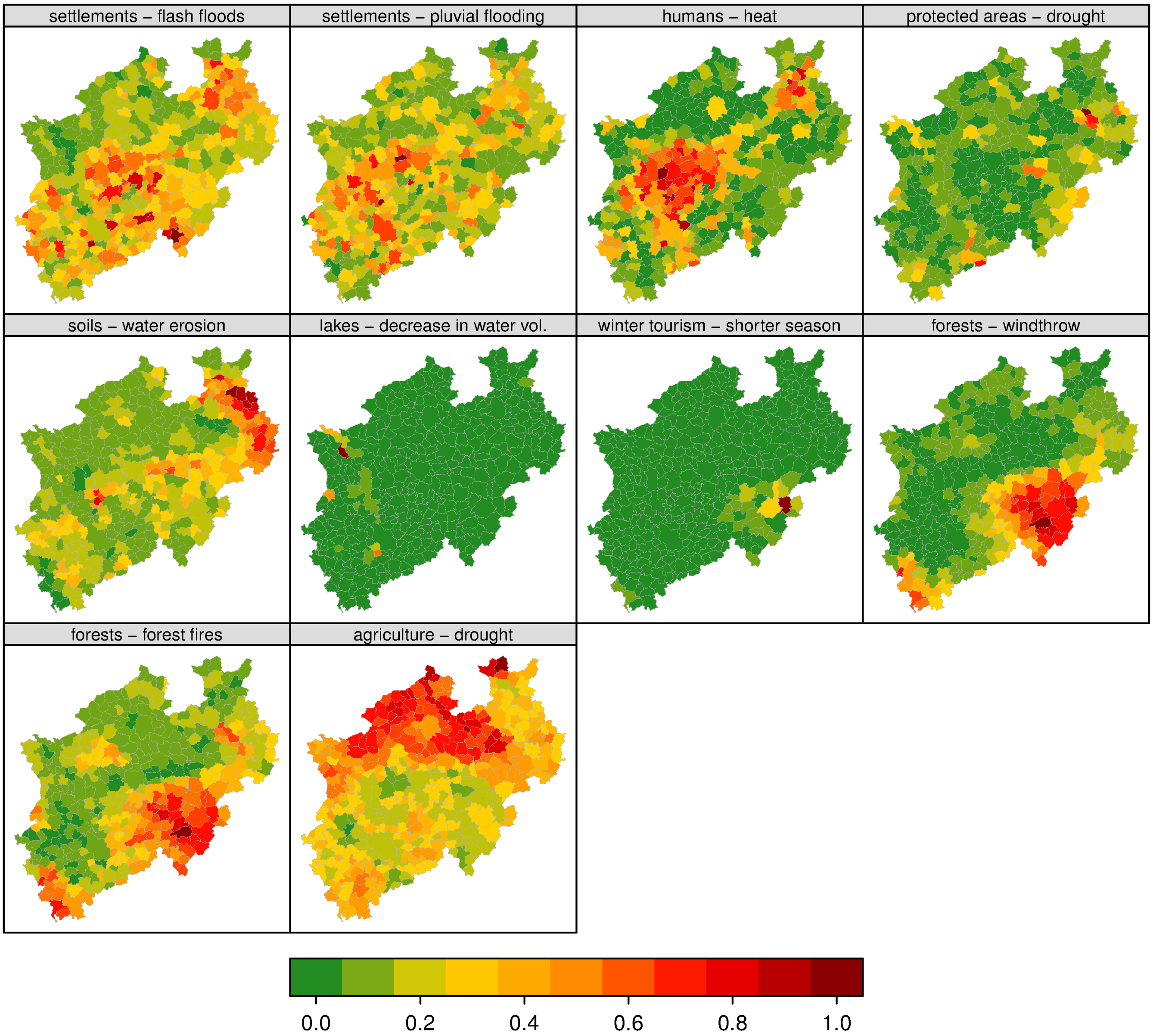

Figure 6: Sensitivity values ranging from 0 (low) to 1 (high). Values are scaled to the data space of municipalities in NRW.

4 Discussion

The presented approach allows for comparative and integrated assessments of climate change vulnerabilities, while enabling a sector-specific perspective of climate change effects. We demonstrate the approach through a multisectoral, regional case study in the German federal state of North Rhine-Westphalia, which exhibits a strong spatial heterogeneity, while being of special relevance for the German economy. Sensitivity is quantified by means of tailor-made approaches for specific sectors for biophysical and socioeconomic dimensions. This is then related directly to relevant exposure indicators, defined as relative changes in climate variables between the past and future based on two regional climate models (CCLM and REMO). This consideration of direct linkages between the exposure unit and specific climatic stimuli has been often neglected in vulnerability analysis before (Preston et al., 2011).

The applied aggregation methodology of exposure and impacts shares common ground with the "vulnerability cube" proposed by Lin and Morefield (2011), who classify vulnerability by means of axes expressing specific indicators in a multidimensional cube. However, they restrict their concept to visualization, whereas we involve a mathematical function of sensitivity, exposure and impacts which can be visualized in a three-dimensional space.

In general, a consensus exists, regarding the meaning of the components of vulnerability between different scientific communities (Costa and Kropp, 2012). However, vulnerability frameworks still remain abstract and lack an indication regarding their aggregation procedure (Hinkel, 2011). We therefore developed a quantitative method to aggregate the components. By multiplying sensitivity and exposure to quantify impacts, we ensure that regions experiencing no climatic changes are indeed

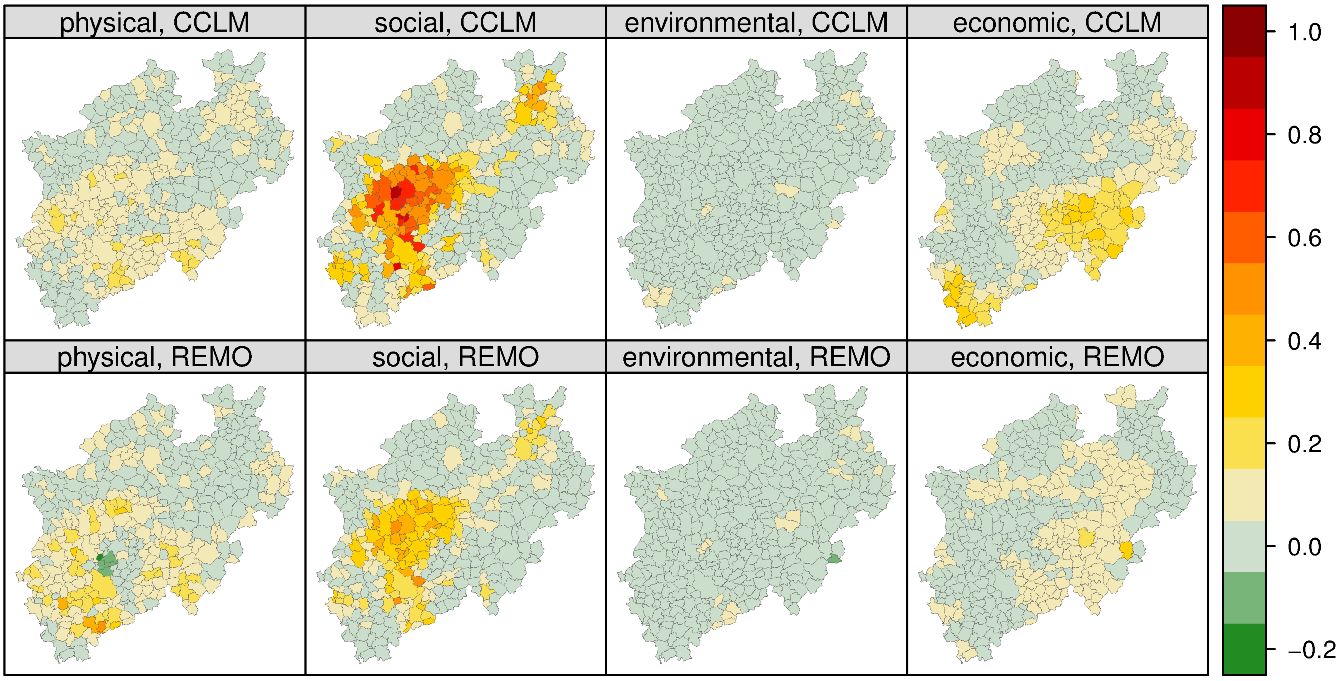

Figure 7: Aggregated potential impacts based on the climate models CCLM (top) and REMO (bottom) for the physical, social, environmental and economic dimension. Values from 0-1 represent adverse impacts, below 0 beneficial impacts. Underlying exposure and sensitivity variables have been scaled to the data space of both models. Exposure is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B.

characterized by zero impacts at the level of sector-specific impacts. After reducing complexity through aggregation, the method enables a cross-sectoral view on the spatial distribution of vulnerability. At the same time, it also allows to track back decisive factors of the system to support target-oriented adaptation measures. Yet, while for sector-specific impacts regions of zero impacts (e.g., due to no climatic changes) are still clearly identifiable, our concept allows for a compensation between impact or sectors, for example between the environmental and economic dimension. This could be refined by considering different weighting factors within the aggregation. However, these differ between regions, presumably even within our study area and between different stakeholder groups questioned. To test the influence of different weighting factors, we have additionally applied factors from the stakeholder perspective derived from a European analysis. This leads to small deviations in the weighting for the economic and physical dimensions, a moderate increase in weight for the environmental and moderate decrease for the social dimension. This has resulted in a very similar spatial pattern of total impacts.

While we applied direct linkages between sensitivities and exposure variables, we express the adaptive capacity in a generic manner. This included cross-sectoral features such as financial resources and education level. Given a more comprehensive database, adaptive capacity could also be integrated in our concept a system specific way, e.g capacity of citizens to adapt to heat waves or sector-specific institutional characteristics. This would then fully complement the integrated approach of our vulnerability assessment.

We have concentrated on the spatial scale of municipalities, thus, if available data on this level were applied, or more fine-scaled information was scaled up to these administrative boundaries. Such subnational spatial level supports the comparability of regions and aggregates regional process and patterns for regional planners and policy-makers. However, up-scaling also entails the levelling-out of local information (Fekete et al., 2010). By focusing on municipalities, individual or household impacts are not represented, nor information on larger spatial scales. Also, for some sectors, the regional spatial boundaries at which key decisions are taken (e.g., forest districts) differ from the universally applied municipal boundaries in our study.

Our methodology is in general transferable to other regions, but the selection of impacts processes should be adapted to the specific regional relevance. This step is crucial as it has a major influence on the results. We considered a wide range of regionally relevant and climate-dependent sectors; however, a fully fledged analysis was not possible. Given a better database, the approach could also be extended for a wider range of sectors. Apart from the spatial geophysical and socioeconomic data we have applied, further information could also be derived from the involvement of stakeholders, especially regarding the quantification of adaptive capacity. This would also alleviate the potential bias of an assessment toward the selection of impacts, which are quantifiable with existing data sources. Further, it has to be stressed that the results of this case study express relative vulnerabilities, which

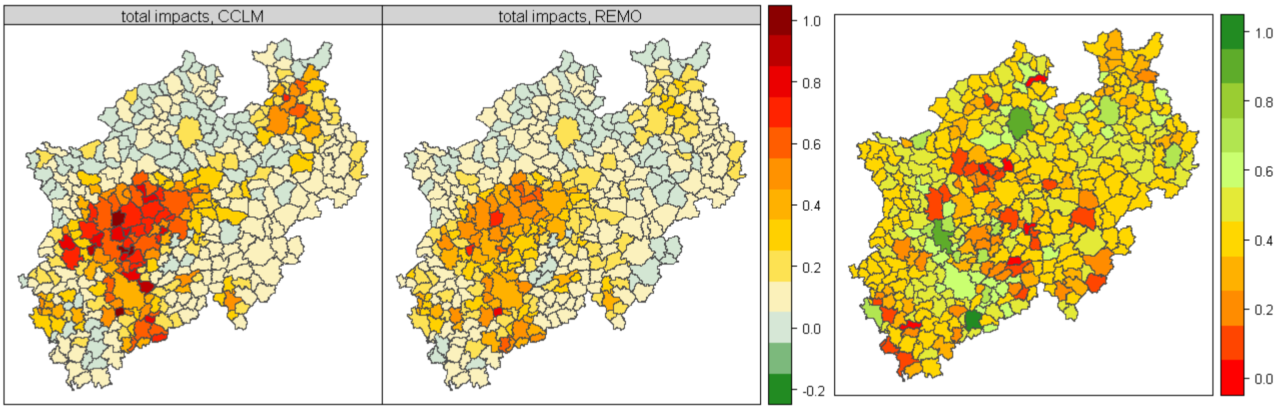

Figure 8: Total potential impacts (left) based on the climate models CCLM and REMO, considering equal weighting factors for the dimensions, and generic adaptive capacity (right). Impact values from 0-1 represent negative impacts, below 0 positive impacts. Values of adaptive capacity range from 0=low to 1=high. Values are scaled to the data space of both models. The exposure included in the impacts is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B.

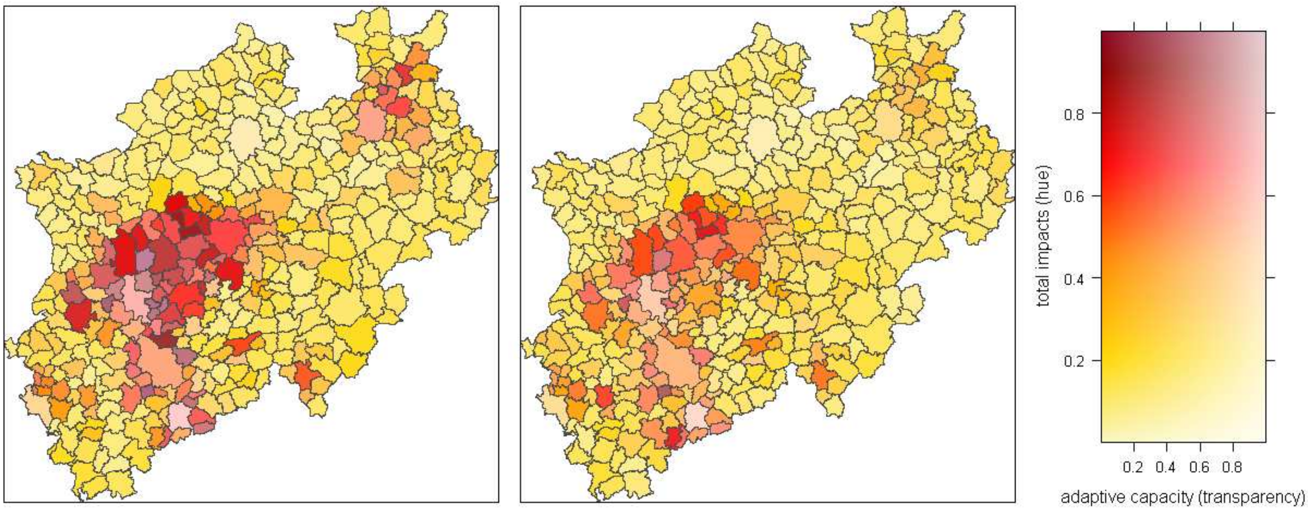

Figure 9: Visualization of vulnerability based on aggregated impacts and the generic adaptive capacity for CCLM (left) and REMO (right). A high adaptive capacity reduces negative impacts (hue from yellow to red), which is visualized by changes in the level of transparency. For the aggregation of the dimensions, equal weighting factors have been applied. The underlying exposure is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B.

only allow for a comparative interpretation of the values within the study area. Thus, zero impacts in a region can also derive from zero sensitivity, as the minimum value within the study area. In this case, climatic impacts still might occur in the region. For some sectors, absolute vulnerabilities or impacts could be determined. This has been achieved by (Klaus et al., 2011) for the windthrow risk in forests of NRW, where sensitivity was directly related to actual past damages occurring during a severe winter storm. However, such data were not available for the full range of sectors analyzed.

We have presented a coherent concept for operationalizing climate change vulnerability assessment in a comparable manner, however, involving both advantages and disadvantages, which are briefly summarized in Tab. 5.

The application of the approach to the region of NRW showed regional impact "hot-spots" in the metropolitan area, the foothills of the mountains and in the East. A higher potential impact of climate change has also been found by Rannow et al. (2010) for the Rhine valley in NRW. However, they conclude a clearer gradient from higher impacts in the West to lower ones in the East of NRW. While the underlying climate projection (REMO, scenario A1B) is comparable, they assume a substitution between low climatic changes and a high sensitivity and apply a set of considered impacts, which deviates considerably from ours. By applying a cluster analysis, Kropp et al. (2006) have also identified most vulnerable areas regarding heat waves in the Rhine-Rhur region, and in the mountainous regions regarding the forestry sector. According to our framework, high specific impacts accrue from both high sensitivities and high exposure coinciding spatially. Regarding our results, this is the case for impacts of heat wave on humans in the metropolitan area and of storms on forest stands in

Table 5: Advantages and disadvantages of the presented approach of a vulnerability assessment

Advantages	Disadvantages
Quantification of aggregated impact burden across sectors	Subjectivity due to selection of impact processes
Integration of biophysical and socioeconomic dimension	Subjectivity due to weighting factors between impacts or sectors
Transparent formalization of procedure	Approach allows for a compensation of positive and negative impacts across sectors
Clear relation between system-specific sensitivities and relevant exposure variables	Interpretation of results is limited to relative comparison within the respective study area
Decisive factors can be traced back to sector-specific impacts, sensitivities or exposures	

the mountains. Further adaptation measures focusing on these impacts could thus reduce the consequence of climate change considerably. Thereby synergies across sectors should be prioritized, which are possible to identify based on our multisectoral approach. For example, the conversion of coniferous dominated forests in the mountains could both reduce the impacts regarding windthrow and forest fires. As a possible adaptation option to heat wave impacts, sealed surfaces especially in the Rhine valley could be reduced, which at the same time, may diminish impacts from floods. In light of the National German Adaptation Strategy enacted in 2008, each Federal States is demanded to develop regional adaptation strategies. A start toward the planning and implementation of adaptation measure for NRW was made with the states strategy, published the following year by the Environmental Ministry (MUNLV, 2009). While a qualitative overview over potential impacts of sectors is provided, it still lacks a comprehensive quantitative approach. Our cross-sectoral analysis fills this knowledge gap and supports the concretization and prioritization regarding specific adaptation measures.

5 Conclusion

While sectoral impact assessments have become common usage in the climate change field, integrated approaches are still scarce. This information, however, is of importance to inform and prioritize adaptation processes and is requested by decision-makers (e.g., Patt et al., 2005; Preston et al., 2011). To initiate informed adaptation, knowledge on several levels is needed. On the one hand, those regions need to be identified which will have to deal with the highest impact burden and therefore have the highest need for adaptation. On the other hand, detailed information on the concrete sectoral impacts and underlying cause-and-effect chains is essential to enable efficient and purposeful adaptation. Knowledge on expected impacts in other sectors in the same location is also important to avoid maladaptation. Our standardized approach allows for a comparative and integrated assessment of climate change impacts with some limitations, while enabling a sector-specific perspective view. We demonstrate the approach through a regional case study in the German federal state of NRW. We show sector-specific differences of impact-severity, and identify spatial hot-spots. Our results give some clear indications toward suitable intervention options in specific sectors. However, various issues of the approach, for example the subjectivity of selection of impacts and the aggregation across sectors still remain unresolved. This stresses the need to consider the aim and methodological advantages and disadvantages before applying any vulnerability assessment.

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