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Climate change vulnerability assessments in the regional context

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Faculty of Mathematics and Natural Sciences at the University of Potsdam, Germany

by
Anne Holsten

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Referees:

Prof. Dr. Jürgen P. Kropp, University of Potsdam, Institute of Earth and Environmental Science; Potsdam Institute for Climate Impact Research

Prof. Dr. Tobia Lakes, Humboldt University of Berlin, Institute for Geography

Dr. habil. Jörn Birkmann, University of Bonn, Institute for Geography; United Nations University, Institute for Environment and Human Security

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Abstract

Adapting sectors to new conditions under climate change requires an understanding of regional vulnerabilities. Conceptually, vulnerability is defined as a function of sensitivity and exposure, which determine climate impacts, and adaptive capacity of a system. Vulnerability assessments for quantifying these components have become a key tool within the climate change field. However, there is a disagreement on how to make the concept operational in studies from a scientific perspective. This conflict leads to many still unsolved challenges, especially regarding the quantification and aggregation of the components and their suitable level of complexity.

This thesis therefore aims at advancing the scientific foundation of such studies by translating the concept of vulnerability into a systematic assessment structure. This includes all components and implies that for each considered impact (e.g. flash floods) a clear sensitive entity is defined (e.g. settlements) and related to a direction of change for a specific climatic stimulus (e.g. increasing impact due to increasing days with heavy precipitation). Regarding the challenging aggregation procedure, two alternative methods allowing a cross-sectoral overview are introduced and their advantages and disadvantages discussed. This assessment structure is subsequently exemplified for municipalities of the German state North Rhine-Westphalia via an indicator-based deductive approach using information from literature. It can be transferred also to other regions. As for many relevant sectors, suitable indicators to express the vulnerability components are lacking, new quantification methods are developed and applied in this thesis, for example for the forestry and health sector.

A lack of empirical data on relevant thresholds is evident, for example which climatic changes would cause significant impacts. Consequently, the multi-sectoral study could only provide relative measures for each municipality, in relation to the region. To fill this gap, an exemplary sectoral study was carried out on windthrow impacts in forests to provide an absolute quantification of the present and future impact. This is achieved by formulating an empirical relation between the forest characteristics and damage based on data from a past storm event. The resulting measure indicating the sensitivity is then combined with wind conditions.

Multi-sectoral vulnerability assessments require considerable resources, which often hinders the implementation. Thus, in a next step, the potential for reducing the complexity is explored. To predict forest fire occurrence, numerous meteorological indices are available, spanning over a range of complexity. Comparing their performance, the single variable relative humidity outperforms complex indicators for most German states in explaining the monthly fire pattern. This is the case albeit it is itself an input factor in most indices. Thus, this meteorological factor alone is well suited to evaluate forest fire danger in many Germany regions and allows a resource-efficient assessment. Similarly, the complexity of methods is assessed regarding the application of the ecohydrological model SWIM to the German region of Brandenburg. The inter-annual soil moisture levels simulated by this model can only poorly be represented by simpler statistical approach using the same input data. However, on a decadal time horizon, the statistical approach shows a good performance and a strong dominance of the soil characteristic field capacity. This points to a possibility to reduce the input factors for predicting long-term averages, but the results are restricted by a lack of empirical data on soil water for validation.

The presented assessments of vulnerability and its components have shown that they are still a challenging scientific undertaking. Following the applied terminology, many problems arise when implementing it for regional studies. Advances in addressing shortcomings of previous studies have been made by constructing a new systematic structure for characterizing and aggregating vulnerability components. For this, multiple approaches were presented, but they have specific advantages and disadvantages, which should also be carefully considered in future studies. There is a potential to simplify some methods, but more systematic assessments on this are needed. Overall, this thesis strengthened the use of vulnerability assessments as a tool to support adaptation by enhancing their scientific basis.

Zusammenfassung (German)

Die Anpassung von Sektoren an veränderte klimatische Bedingungen erfordert ein Verständnis von regionalen Vulnerabilitäten. Vulnerabilität ist als Funktion von Sensitivität und Exposition, welche potentielle Auswirkungen des Klimawandels darstellen, und der Anpassungsfähigkeit von Systemen definiert. Vulnerabilitätsstudien, die diese Komponenten quantifizieren, sind zu einem wichtigen Werkzeug in der Klimawissenschaft geworden. Allerdings besteht von der wissenschaftlichen Perspektive aus gesehen Uneinigkeit darüber, wie diese Definition in Studien umgesetzt werden soll. Aus diesem Konflikt ergeben sich viele Herausforderungen, vor allem bezüglich der Quantifizierung und Aggregierung der einzelnen Komponenten und deren angemessenen Komplexitätsniveaus.

Die vorliegende Dissertation hat daher zum Ziel die Anwendbarkeit des Vulnerabilitätskonzepts voranzubringen, indem es in eine systematische Struktur übersetzt wird. Dies beinhaltet alle Komponenten und schlägt für jede Klimaauswirkung (z.B. Sturzfluten) eine Beschreibung des vulnerablen Systems vor (z.B. Siedlungen), welches direkt mit einer bestimmten Richtung eines relevanten klimatischen Stimulus in Verbindung gebracht wird (z.B. stärkere Auswirkungen bei Zunahme der Starkregentage). Bezüglich der herausfordernden Prozedur der Aggregierung werden zwei alternative Methoden, die einen sektorübergreifenden Überblick ermöglichen, vorgestellt und deren Vor- und Nachteile diskutiert. Anschließend wird die entwickelte Struktur einer Vulnerabilitätsstudie mittels eines indikatorbasierten und deduktiven Ansatzes beispielhaft für Gemeinden in Nordrhein-Westfalen in Deutschland angewandt. Eine Übertragbarkeit auf andere Regionen ist dennoch möglich. Die Quantifizierung für die Gemeinden stützt sich dabei auf Informationen aus der Literatur. Da für viele Sektoren keine geeigneten Indikatoren vorhanden waren, werden in dieser Arbeit neue Indikatoren entwickelt und angewandt, beispielsweise für den Forst- oder Gesundheitssektor.

Allerdings stellen fehlende empirische Daten bezüglich relevanter Schwellenwerte eine Lücke dar, beispielsweise welche Stärke von Klimaänderungen eine signifikante Auswirkung hervorruft. Dies führt dazu, dass die Studie nur relative Aussagen zum Grad der Vulnerabilität jeder Gemeinde im Vergleich zum Rest des Bundeslandes machen kann. Um diese Lücke zu füllen, wird für den Forstsektor beispielhaft die heutige und zukünftige Sturmwurfgefahr von Wäldern berechnet. Zu diesem Zeck werden die Eigenschaften der Wälder mit empirischen Schadensdaten eines vergangenen Sturmereignisses in Verbindung gebracht. Der sich daraus ergebende Sensitivitätswert wird anschließend mit den Windverhältnissen verknüpft.

Sektorübergreifende Vulnerabilitätsstudien erfordern beträchtliche Ressourcen, was oft deren Anwendbarkeit erschwert. In einem nächsten Schritt wird daher das Potential einer Vereinfachung der Komplexität anhand zweier sektoraler Beispiele untersucht. Um das Auftreten von Waldbränden vorherzusagen, stehen zahlreiche meteorologische Indices zur Verfügung, welche eine Spannbreite unterschiedlicher Komplexitäten aufweisen. Bezüglich der Anzahl monatlicher Waldbrände weist die relative Luftfeuchtigkeit für die meisten deutschen Bundesländer eine bessere Vorhersagekraft als komplexere Indices auf. Dies ist er Fall, obgleich sie selbst als Eingangsvariable für die komplexeren Indices verwendet wird. Mit Hilfe dieses einzelnen meteorologischen Faktors kann also die Waldbrandgefahr in deutschen Region ausreichend genau ausgedrückt werden, was die Ressourceneffizienz von Studien erhöht.

Die Methodenkomplexität wird auf ähnliche Weise hinsichtlich der Anwendung des ökohydrologischen Modells SWIM für die Region Brandenburg untersucht. Die interannuellen Bodenwasserwerte, welche durch dieses Modell simuliert werden, können nur unzureichend durch ein einfacheres statistisches Modell, welches auf denselben Eingangsdaten aufbaut, abgebildet werden. Innerhalb eines Zeithorizonts von Jahrzehnten, kann der statistische Ansatz jedoch das Bodenwasser zufriedenstellend abbilden und zeigt eine Dominanz der Bodeneigenschaft Feldkapazität. Dies deutet darauf hin, dass die Komplexität im Hinblick auf die Anzahl der Eingangsvariablen für langfristige Berechnungen reduziert werden kann. Allerdings sind die Aussagen durch fehlende beobachtete Bodenwasserwerte zur Validierung beschränkt.

Die vorliegenden Studien zur Vulnerabilität und ihren Komponenten haben gezeigt, dass eine Anwendung noch immer wissenschaftlich herausfordernd ist. Folgt man der hier verwendeten Vulnerabilitätsdefinition, treten zahlreiche Probleme bei der Implementierung in regionalen Studien auf. Mit dieser Dissertation wurden Fortschritte bezüglich der aufgezeigten Lücken bisheriger Studien erzielt, indem eine systematische Struktur für die Beschreibung und Aggregierung von Vulnerabilitätskomponenten erarbeitet wurde. Hierfür wurden mehrere Ansätze diskutiert, die jedoch Vor- und Nachteile besitzen. Diese sollten vor der Anwendung von zukünftigen Studien daher ebenfalls sorgfältig abgewogen werden. Darber hinaus hat sich gezeigt, dass ein Potential besteht einige Ansätze zu vereinfachen, jedoch sind hierfür weitere Untersuchungen nötig. Insgesamt konnte die Dissertation die Anwendung von Vulnerabilitätsstudien als Werkzeug zur Unterstützung von Anpassungsmanahmen stärken.

Contributing scientific publications

Publications in peer-reviewed and ISI-listed journals:

Holsten A., Dominic A.R., Costa L., Kropp J.P. (2013): Evaluation of the Performance of Meteorological Forest Fire Indices for German Federal States, Forest Ecology and Management, 287(1): 123-131

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

Lissner T., Holsten A., Walther C., Kropp J.P. (2012): Towards sectoral and standardised vulnerability assessments: the example of heatwave impacts on human health. Climatic Change, 112(3-4): 687-708

Olonscheck M., Holsten A., Kropp J.P. (2011): Heating and cooling energy demand and related emissions of the German residential building stock under climate change. Energy Policy, 39(9): 4795-4806

Klaus M., Holsten A., Hostert P., Kropp J.P. (2011): An integrated methodology to assess windthrow impacts on forest stands under climate change. Forest Ecology and Management, 261(11): 1799-1810

Rybski D., Holsten A., Kropp J.P. (2011): Towards an unified characterization of phenological phases: fluctuations and correlations with temperature, Physica A, 390(4): 680-688

Holsten A., Vetter T., Vohland K., Krysanova V. (2009): Impact of climate change on soil moisture dynamics in Brandenburg with a focus on nature conservation areas. Ecological Modelling, 220(17): 2076-2087

Peer-reviewed book chapters:

Holsten A., Walther C., Rothmeier O., Kropp J.P.: Integrated Assessment of Vulnerability to Climate Change: The case study of North-Rhine Westphalia. In: Schmidt-Thomé P., Greiving S. (eds.): European climate vulnerabilities and adaptation: A spatial planning perspective, Wiley-Blackwell, Chichester, 352 p. (in press).

Walther C., Holsten A., Kropp J.P.: Identifying a typology of climate change in Europe. In: Schmidt-Thomé P., Greiving S. (eds.): European climate vulnerabilities and adaptation: A spatial planning perspective, Wiley-Blackwell, Chichester, 352 p. (in press).

Lindner C., Holsten A.: Climate change exposure assessment of European regions, In: Schmidt-Thomé P., Greiving S. (eds.): European climate vulnerabilities and adaptation: A spatial planning perspective, Wiley-Blackwell, Chichester, 352 p. (in press).

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1

General Introduction

1.1 Background

Climate change has become a major global challenge, especially regarding its consequences for the natural and human systems (IPCC, 2007). Even under the premise of ambitious mitigation efforts, such as limiting global warming to 2 °C, climate change will still continue to take place during the next decades (Friedlingstein et al., 2011). The current inertia in international mitigation negotiations makes an acceleration and intensification of climatic changes even more likely (Rogelj et al., 2011). A global warming beyond 4 °C for example, would lead to severe consequences for both ecosystems and social systems (New et al., 2011; The World Bank, 2012).

In addition to implementing mitigation measures, adapting to future conditions is an essential response to alleviate negative consequences for vulnerable regions or populations. However, for the development and prioritization of adaptation strategies and measures, the identification and analysis of potential fields of actions is needed. This can be supported by comprehensive information about regional vulnerabilities over a wide range of sectors by analyzing the expected climatic changes, the systems's properties regarding these changes and the potential capacity for responding or coping. Quantification of these aspects of vulnerability is crucial for reducing harm from climatic changes (Birkmann, 2006). To sum up, “adaptation requires an understanding of vulnerabilities” (Bierbaum et al., 2007).

1.1.1 Terminology of vulnerability

Vulnerability is a central concept within the climate change field and many related research fields such as the natural hazards, risk management or development community (Füssel, 2007). Yet, its definition has been the subject of extensive scientific debate. Until today, no universal definition has been agreed upon, rather several concepts have been developed within various scientific communities (for an overview see WeADAPT, 2011). Nevertheless, they agree upon vulnerability as a “measure of possible future harm”, for example due to climatic changes (Hinkel, 2011). Further, vulnerability has been often understood in a general sense, crossing various spatial and temporal scales (Malone and Engle, 2011).

The existing concepts can be separated into “top-down” and “bottom-up” approaches (O'Brien et al., 2004a). The first, traditionally focused on the biophysical effects of climate change from the perspective of emissions leading to changes which are then translated into impacts and vulnerabilities. This can thus also be termed an “end-point” assessment, where vulnerability is the final outcome, or “impact driven vulnerability studies” (Ford et al., 2010). The bottom-up perspective emphasizes social aspects influencing vulnerability and often applies vulnerability in the sense of the “starting-point” of an assessment.

The heterogeneous and often vague definitions of vulnerability have, until today, led to much confusion (Ionescu et al., 2008), although commonalities in the meaning and operation of concepts across research fields have been identified (Costa and Kropp, 2013). Despite this weakness, however, the concept remains appealing as it is commonly understood as integrating the biophysical and social sphere (Polsky et al., 2007).

Within the climate change community, vulnerability is often defined as follows (IPCC, 2001a;

Füssel and Klein, 2006):

Vulnerability is "the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity".
Sensitivity is the "nature and degree to which a system is exposed to significant climatic variations".
Sensitivity and exposure lead to **impacts** as "consequences of climate change on natural and human systems."
Adaptive capacity is "the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences."
Vulnerability **components** are thus exposure, sensitivity, impacts and adaptive capacity.
The vulnerability can be differentiated between **sectors**, such as agriculture or forestry.

Thus, vulnerability is seen as a function of the components adaptive capacity and impacts, which in turn are expressed by the sensitivity and exposure (Figure 1.1). Evaluating the impacts of a system would therefore include its sensitivity and related exposure, whereas the vulnerability also encompasses the adaptive capacity.
This terminology has been previously applied for example in the third and fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001b, 2007), which formed the basis of numerous climate related studies (e.g. Schröter et al., 2005b; O'Brien et al., 2004b). Sensitivity is regarded in a broad sense, as it includes the relation of any system to any direct or indirect climate-related stimuli. The exposure includes the "nature and degree" of climatic changes, which could be expressed by the magnitude, however this is not clearly specified. This highlights, that the terms used to define the components are themselves vague (Costa and Kropp, 2013). Adaptive capacity refers to the coping capacity and the preparedness. Although not included directly in this framework, adaptation is seen as the key to reducing vulnerability by a system's response and is therefore distinguished from adaptive capacity (Hufschmidt, 2011).

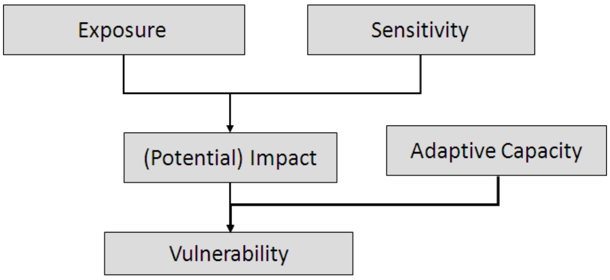

Figure 1.1: Vulnerability framework commonly applied in the climate change community with its components exposure, sensitivity, impacts and adaptive capacity, after Füssel and Klein (2006) and IPCC (2001a).

1.1.2 Vulnerability assessment as a tool in the climate change community

The above described vulnerability concept with its components can be regarded as a theoretical framework in the climate change context. Such frameworks are commonly "aimed at providing guidance to those conducting vulnerability assessments or measuring the costs and benefits of adaptation" (Ionescu et al., 2008). In other words, they are then translated into qualitative or quantitative assessments, which address consequences of climate change and have been suggested as a tool to include aspects of climate change into planning and risk management (Preston et al., 2008). Similarly, Schröter et al. (2005b) and Füssel and Klein (2006) argue that the goal of such assessments ins informing decision makers to initiate adaptation options or policies to alleviate adverse effects of climate change. Under this common objective, two main lines of assessments have been followed: enhancing the understanding of vulnerability related processes (problem-oriented) and, based on this understanding, directly supporting the decision-making process (Preston et al., 2011).

Several guidelines have been developed, which outline practical and analytical steps for conducing such studies.

Already in the 90's, Carter et al. (1994) defined seven steps for climate impact assessments for the IPCC. These include defining the problem, selecting methods and scenarios, assessing biophysical and socioeconomic impacts and autonomous adjustments and finally evaluating adaptation options.

In the following years a shift from mere impact assessments to vulnerability assessments has occurred. For these, Schröter et al. (2005b) have defined a minimal set of methodological requirements and developed an eight-step approach for an assessment focusing on informing stakeholders. Similarly Smit and Wandel (2006) have proposed a framework for a participatory vulnerability assessment for application with communities. In a more detailed manner, Polsky et al. (2007) have elaborated one of the eight steps proposed by Schröter et al. (2005b) - the selection of indicators - and have developed the "vulnerability scoping diagram". It serves as a structure to support the comparability between studies based on case-specific measures of exposure, sensitivity and adaptive capacity.

While these approaches give guidance for the implementation, their suggestions remain very general and lack information on aggregation procedures.

A different formalization was followed by Ionescu et al. (2008) who present a mathematical framework for vulnerability based on the definitions given above. This approach entails a transition function from one state to another under the influence of a hazard. Sensitivity and adaptive capacity are presented as inherent complex characteristics of the system. The first can be included in the concept given a differentiability of the transition function. Adaptive capacity comprises the set of effective actions at hand to a system.

In addition to this, Luers (2005) also propose an analytical assessment framework. They express vulnerability with a three-dimensional vector of exposure, sensitivity, adaptive capacity and propose system-specific threshold value above which harmful consequences occur.

In summary, "the term vulnerability remains abstract, ambiguous, and plastic" (Malone and Engle, 2011). However, starting from the common general framework (see Figure 1.1), assessment approaches have been proposed. These can provide a structure or guidance for conducting vulnerability studies and have advanced the scientific debate. The following sections will provide more detailed insights into these assessments, while focusing on the terminology of vulnerability provided above, as commonly applied in the climate change community.

1.1.3 Vulnerability assessments are en vogue

The number of scientific vulnerability publications related to climate change has soared in recent years; from around 80 studies carried out before the year 2000 to over 160 studies published in 2012 alone[1]. An overview of key studies and their general methodology will be provided in the following sections. They can be broadly grouped into simulation-model based (complex algorithms to simulate climate impacts, e.g. dynamical vegetation models) and indicator based approaches (in the sense of defining simple key indicators for the vulnerability components as separate proxies and aggregating these afterwards). It has to be noted that this separation is not sharp and both lines are combined in some assessments.

An example for an indicator-based assessment is the quantitative Europe-wide analysis of vulnerability of regions to climate change including multiple sectors carried out by Greiving et al. (2011b). Further, several general vulnerability indices have been developed to compare the situation between countries (e.g. Moss et al., 2001; Brooks et al., 2005). However, they have been criticized due to their hiding of the actual vulnerability creating processes, which happen at finer scales (e.g. Eriksen and Kelly, 2006).

Others have focused on specific sectors or systems or concentrated on finer scales, such as rural communities in India (Pandey and Jha, 2011), agriculture in India (O'Brien et al., 2004b), bushfires

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[1] According to the database "Web of Knowledge" (Thomson Reuters), based on the following search algorithm: "vulnerability SAME assessment climate".

in Australia (Preston et al., 2008), the tourism sector on a global scale (Perch-Nielsen, 2010) and coastal cities (Yoo et al., 2011).

Qualitative approaches to vulnerability components include for example studies on the forestry sector in Canada (Johnston and Williamson, 2007) or Europe (Lindner et al., 2010).

Simulation-based methods have been for example applied in a Europe-wide study on losses of ecosystem services due to global change, in which results from spatially explicit dynamical ecosystem models were integrated into impact maps (Schröter et al., 2005a; Metzger and Schröter, 2006). Model results (e.g. changes in carbon storage of ecosystems) are then combined with adaptive capacity values to produce vulnerability maps.

Also, on a European scale, Ciscar et al. (2011) evaluated the physical and economic consequences of climate changes based on sectoral physical-impact models. These were then fed into economic models yielding monetary welfare losses.

On a global scale, a United Nations study has quantified ecological, agro-economic and social vulnerability by means of simulation results for each of these (e.g. changes in natural vegetation based on a dynamical vegetation model indicate the ecological vulnerability) (Bierbaum et al., 2007). Similarly, the “Climate Vulnerability Monitor” has quantified vulnerabilities for 184 countries regarding environmental disasters, habitat change, health impact and industrial stress based on simulation results for each of these dimensions (DARA, 2012). Although both of these global studies base their definition of vulnerability on Füssel and Klein (2006), the adaptive capacity is not included consistently.

In Germany, the political debate regarding adaptation has only been ongoing for a few years. Adaptation was integrated into the political process only after the mitigation debate, first by considering the issue as part of the mitigation strategy in 2005, and finally in 2008 with the National Adaptation Strategy (Stecker et al., 2012). Meanwhile, climate change vulnerability and impact assessment have moved from the scientific field into practice and have become a common tool in the adaptation discourse of the political arena (Patt et al., 2005).

A vulnerability assessment, for example, was conducted for German regions aiming at providing a knowledge basis for the German Strategy for Global Change (Zebisch et al., 2005). Furthermore, many studies were conducted for single German federal states and regions, which focused on supporting the drafting of regional adaptation strategies. This has started with an analysis of future climatic changes for the state of Saxony and an impact assessments for the state of Brandenburg in the year 2003 (for an overview of adaptation strategies and vulnerability and impact assessment for German federal states see also: Klimabündnis, 2012; ARL, 2009). To date, almost all states have analyzed relevant regional climate impacts or vulnerabilities and the majority have published adaptation action plans or strategies.

1.1.4 Key challenges

The overview above has shown, that although numerous studies have been previously conducted, a discussion on adequate and common methods is still lacking (Schröter et al., 2005b). A meta-study carried out for the climate change impact, adaptation and vulnerability studies listed in the European Chapter of the Fourth Assessment Report of the IPCC (Alcamo et al., 2007) revealed that for some sectors, appropriate methods are still in the development phase (Hofmann et al., 2011). Further progress is therefore needed regarding the implementation of vulnerability assessments, which can be broadly grouped into the following key scientific challenges:

Quantifying vulnerability components

The quantification of vulnerability components requires a notion on the vulnerable entity, the stimulus and a direction of the change (“worse” or “better”) (Ionescu et al., 2008). In other words, while extended scientific debated have pursued the question “What is vulnerability?”, for vulnerability assessments the crucial questions to be addressed are rather: “Who or what is vulnerable?” and “vulnerable to what?” (Malone and Engle, 2011; Füssel, 2007). As straightforward as this may seem, these questions are often disregarded in vulnerability studies. A meta-analysis of vulnerability mapping studies has revealed a “lack of specificity regarding what systems or system components are vulnerable and to what” (Preston et al., 2011).

A vulnerability assessment for European regions shows that the identification of sensitivity entities and relevant stimuli is difficult to achieve for a wide range of sectors (Greiving et al., 2011b). Moreover, the components of vulnerability are not consistently implemented. For example, as a proxy for the sensitivity of forests to fires, the number of past forest fires is applied, which actually represents a measure for the impacts in the past (including the climatic conditions).

In a vulnerability mapping study for Southern Africa, unspecific indicators of exposure (including various climatic stimuli) are combined in an aggregated manner with a set of sensitivity indicators (Midgley et al., 2011). This way, the relationships between specific stimuli and sectoral sensitivities are ignored.

A further simplified approach has been followed in a climate vulnerability index for European regions, presented by the Directorate-General for Regional and Urban Policy of the EU (DG Regio, 2008). Although vulnerability is defined in the report based on the definitions given above, the index is based on an inconsistent mixture of exposure, sensitivity and impact indicators. Thus, the vulnerable entity and the corresponding climatic stimuli remain unclear.

Aggregating procedures

Vulnerability is here defined as a function of its components exposure, sensitivity and adaptive capacity. The acknowledgment of these different components often lead to studies in which they are represented and aggregated by simple indicators. However, the relationship and dynamics between these components remains unclear (Soares et al., 2012). The aggregation of indicators involves weighting factors and represents a major challenge in such assessments (Barnett et al., 2008).

Hinkel (2011) asks for cautiousness regarding the disaggregation of vulnerability into these components as a “blue print” for vulnerability assessments. He argues that the distinction between the components is difficult in real cases (attributing indicators to which component). This is also highlighted by Polsky et al. (2007) who conclude that the vulnerability components are often coupled and difficult to disentangle and note that “expertise with many distinct methods does not necessarily ensure expertise in cobbling the methods together”. However, indicator-based quantifications can indeed be appropriate tools when carried out at local scales, where the system is more straightforward, such that the vulnerable entity can be represented by a smaller set of variables (Hinkel, 2011).

Various studies have engaged in the identification of key indicators of vulnerability components and their aggregation. For example Preston et al. (2008) have exemplified a conceptual model of exposure, sensitivity, and adaptive capacity indicators for bushfires in Australia. The aggregation is carried out by using the arithmetic mean, with different weighting factors. Yoo et al. (2011) have presented an indicator-based approach to quantify vulnerability for counties of a coastal city in South Korea. Sectoral sensitivities were calculated for all counties within a region based on their respective share of land.

While these studies have proposed a framework for the aggregation of components, only a relative quantification was achieved (e.g. by re-scaling the values based on percentiles of the data set). Also, they lack a framework for a cross-sectoral aggregation.

Identifying a suitable level of complexity

Conducting such assessments still requires, among other things, an interdisciplinary research background, a wide range of data sources and sufficient resources, in particular time. One the one hand, experiences from a multi sectoral vulnerability assessment have shown that results from complex assessments are harder to convey to stakeholders and involve unreasonable assumptions (Patt et al., 2005). On the other hand, less complex vulnerability assessments have been often criticized for being too simplistic from the scientific perspective, for example implying stylized representations of exposure and sensitivity

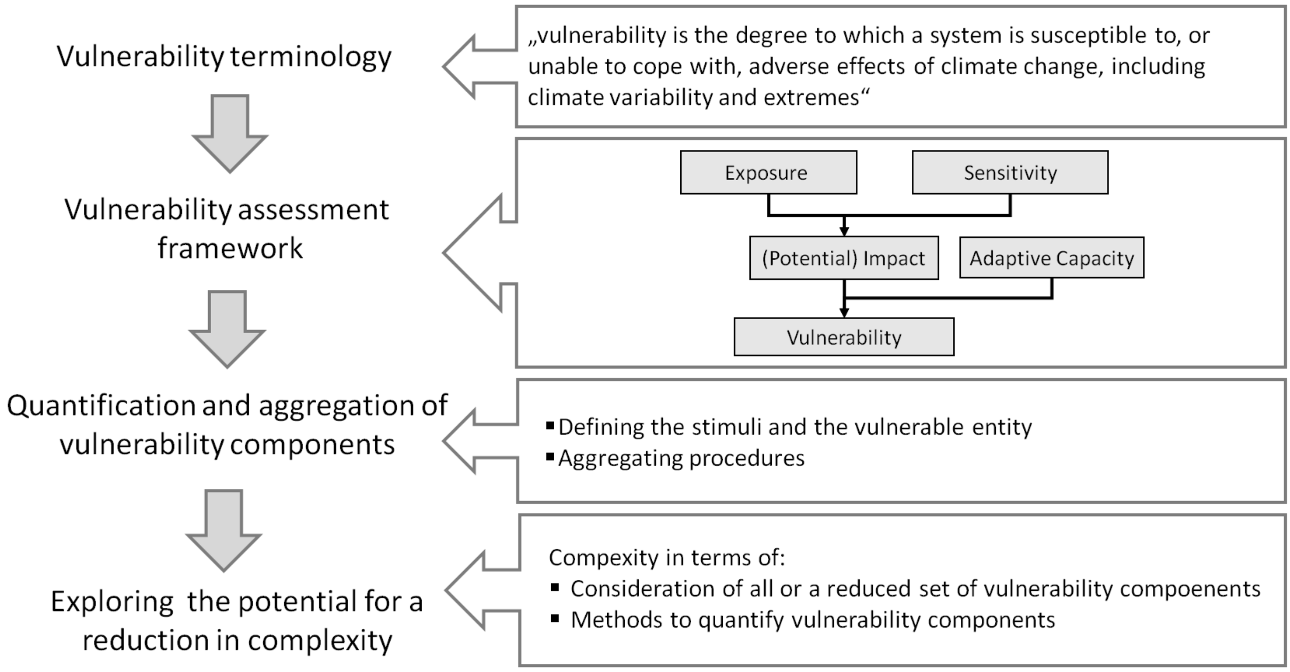

Figure 1.2: Motivation of the thesis: Making progress from vulnerability definitions towards assessment frameworks to the scientific implementation of a vulnerability assessments. Given the great complexity of these, an urging issue is to explore the potential for a reduction in complexity. The corresponding features on the right side refer to the vulnerability definition and framework on which this thesis is based (see Figure 1.1).

(Polsky et al., 2007).
A challenge therefore lies in the expression of the complex concept of vulnerability by means of appropriate measures. Adger (2006) notes that although the concept is easily understandable from a personal view, the difficulty lies in translating it into concrete and quantitative measures without loosing the essential complexity of the system. Studies systematically analyzing the level of complexity of vulnerability assessments are lacking.

1.2 Motivation of the thesis

The preceding discussion on the state-of-the-art showed that the concept of vulnerability has become an essential part of the climate change research. A theoretical framework has been developed in this community to provide guidance for assessing vulnerabilities (see Figure 1.1). Vulnerability assessments have been commonly suggested in the scientific field as a tool to support decision and policy makers in identifying adaptation options (e.g. Schröter et al., 2005b; Füssel and Klein, 2006). A subsequent realization of numerous recent assessments by scientists has been mainly driven by a demand from the political field (Patt et al., 2008).
However, the current applications still fall short of this goal since the concept of vulnerability is strongly debated and a consensus is lacking on how to transform it to actually support prioritization in adaptation politics (Nelson et al., 2010b). Moreover, from the scientific perspective, key challenges still remain unsolved in current applications.
A reason for these shortcomings is that while the definition of vulnerability as a function of exposure, sensitivity and adaptive capacity is on the one hand straightforward, on the other hand it is difficult to implement in assessments (Ionescu et al., 2008). Thus, “today, operationalising vulnerability is a major challenge. Currently, there is no standardised procedure for measuring vulnerability (qualitatively or quantitatively)” (Hufschmidt, 2011). This is also highlighted by Polsky et al. (2007), who point out that the main challenge is not the development of new vulnerability concepts but the methodological integration between research fields.

Vulnerability assessments thus require a sound scientific basis and applicability. From the scientific perspective, the discussion above on how to make the existing concept operational has pointed out major scientific challenges especially regarding the quantification and aggregation of vulnerability components. Therefore, the question arises, how far can science advance in providing sound results from vulnerability assessments with useful results to support adaptation? Several studies focusing on directly supporting high-level political adaptation strategies have been conduced (e.g. DG Regio, 2008; Midgley et al., 2011), however they are weak regarding their scientific foundation as discussed above. From a more analytical perspective, complex frameworks have been proposed (e.g. Ionescu et al., 2008; Luers, 2005). However, they are difficult to implement in case studies as they lack indications on crucial methodological steps, such as the selection of methods or the aggregation of components or require extensive data sources for constructing the vulnerability functions.

This thesis therefore aims at advancing the scientific basis of vulnerability assessments, while providing an applicable implementation for regional studies, using the terminology of vulnerability common in this community (IPCC, 2001a; Füssel and Klein, 2006). For this, a systematic structure is required to enhance comparability and transferability between studies and regions, which has been identified as a crucial feature of these assessments (Polsky et al., 2007). In other words, without such a structure, results from these assessments run the risk of being arbitrary and inconsistent. This then allows the generalization of information from different vulnerability studies.

In this thesis a structure to aid the implementation of a vulnerability assessment is therefore presented, which takes into account the deterministic processes related to climatic changes (such as the processes of climatic stimuli acting upon sensitive entities). The applicability of this systemic approach will then be exemplified for a multi-sectoral assessment.

While this moves forward the implementation of vulnerability assessments, they are still fraught with great complexity. Compromises are therefore commonly made and key scientific challenges neglected or only partly considered. Studies analyzing methods of different complexity to evaluate vulnerability or its components are lacking, e.g. a systematic comparison of possible methods for quantifying components in order to identify a suitable level of complexity. Furthermore, a discussion is missing about whether vulnerability assessments are always the optimal tool to support adaptation or whether the entity of interest could also be reduced to specific vulnerability components, such as exposure or sensitivity.

While investigating the operation of vulnerability components in assessment studies, Costa and Kropp (2013) conclude that breaking the vulnerability down to case studies can help to shape the concept for practical applications. This is particular relevant since bounding assessments to specific settings is necessary to manage problems in the scientific community and among stakeholders (Preston et al., 2011).

This leads to the general motivation of this thesis which is in translating vulnerability definitions and frameworks to the scientific implementation of a vulnerability assessment. This is achieved by advancing the quantification and aggregation of vulnerability components and exploring the potential for a simplification of assessments, which is graphically summarized in Figure 1.2. Based on the assumption that case studies can help to systematically assess specific unsolved challenges and explore possible advances, the present thesis focuses on specific study regions in Germany, for which a “top-down” assessment type will be followed . This motivation will be further elaborated by the following key research questions.

1.3 Research Questions

Based on the vulnerability framework introduced above, approaches are in demand to make it operational and overcome key scientific challenges described above. Along these main lines, the following hypothesis and related research questions are posed:

Hypothesis I: The presented theoretical vulnerability framework allows for multiple approaches of operationalizing the quantification and aggregation of vulnerability components.

⇒ RQ1: How to quantify components of vulnerability?

⇒ RQ2: How to combine components of vulnerability and sectoral impacts?

To address these questions, a multi-sectoral assessment for municipalities of the German federal state of North Rhine-Westphalia is carried out including all components of vulnerability as demanded by the applied framework. This region is suitable to exemplify a multi-sectoral evaluation, since a wide range sectors play a relevant role in this state, which are distributed over a complex spatial setting. As the state is very densely populated and at the same time exhibits a strong economic power, possible consequences of climate change would have a strong impact also for Germany.

The following aspects are particularly focused on in this case study: The vulnerable entity and the relevant stimuli are identified for all sectors by defining the boundaries specific to the sector and the regional setting. Each impact is quantified by tailor-made methods. Moreover, the thesis proposes a framework for the aggregation of the vulnerability components and critically discusses two alternative approaches for a cross-sectoral aggregation.

This vulnerability assessment framework is applied to the study region, but the approach is in principle transferable to other regions. While it enables a spatial comparison between the municipalities, absolute statements on the level of vulnerability are not possible due to a lack of empirical data. This gap is then bridged by a sectoral study on the climate impacts of windthrow in forests in same federal state. Here, an approach for an absolute quantification is shown based on available empirical damage data.

Such an inclusive approach of a multi-sectoral assessment is fraught with considerable resources and requires strong interdisciplinary scientific work. Although vulnerability assessments have become common practice, their application is often hindered by exactly these constraints. Thus, an assessment of a reduction in complexity is required, while at the same time fulfilling the main aim of these assessments in providing a sound basis to implement adaptation measures. Therefore the following second hypothesis and related question are posed:

Hypothesis II: There is a potential to reduce the complexity in vulnerability assessments, while still ensuring an adequate representation of the system to support adaptation responses.

⇒ RQ3: How much complexity is needed regarding the number of components and the applied quantification methods?

The second part of the thesis therefore presents a series of sectoral studies to investigate the potential of a reduction in complexity of such assessments. This will focus on two methods: an indicator-based assessment and a simulation-based assessment.

In the first case, commonly used indicators of fire danger are systematically compared regarding their predicative power of monthly fire pattern of German federal states. These indicators differ strongly in terms of the complexity of their underlying algorithms, which allows the juxtaposition of both performance and complexity. A second study, carried out for the German federal state of Brandenburg, provides insights into the potential to reduce the complexity of a model to represent plant available soil moisture levels by identifying the dominating influencing factors.

1.4 Structure of this thesis

This thesis is written cumulatively. In the introductory chapters above, the state-of-the-art regarding vulnerability assessments and research gaps have been outlined, on which this thesis focuses. The presented research questions are addressed in the following chapters, each of them published in a peer-reviewed journal or book. The full reference to the publication is given

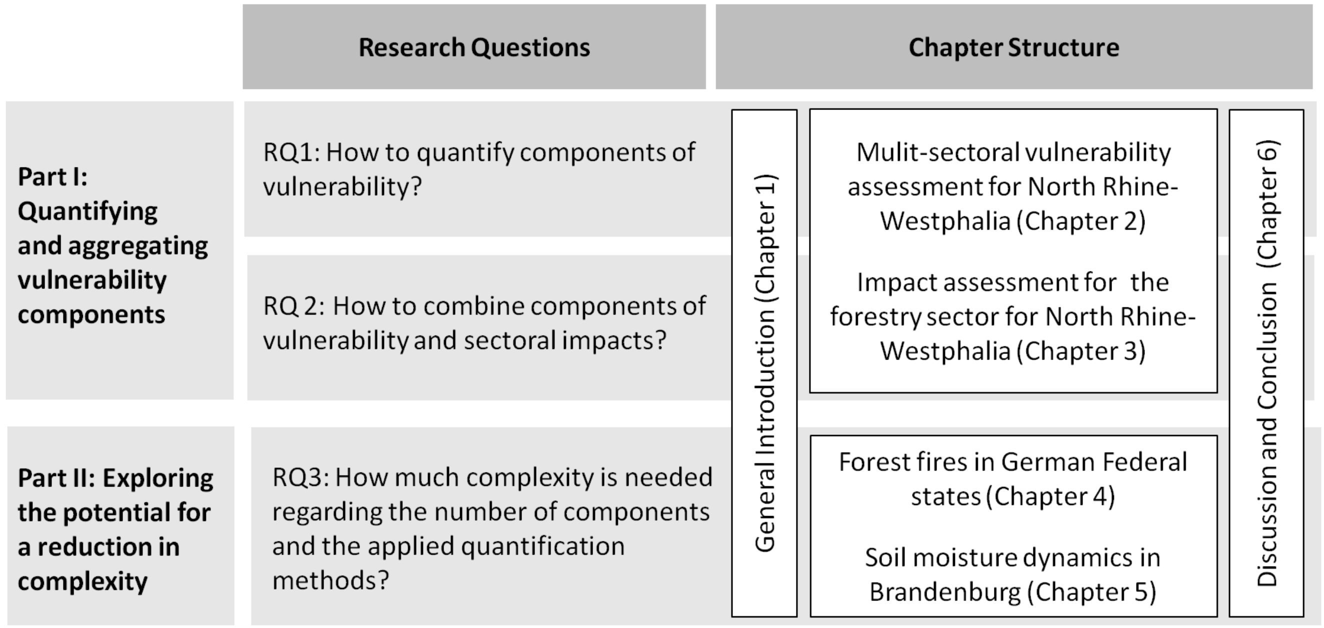

Figure 1.3: Research questions and their relation to the subsequent chapters. For readability the chapter titles are short forms of the original titles as given by the chapter headings.

below the abstract of the respective chapter.
The findings of this thesis in relation to the posed research question are discussed in the chapter following the publications in a critical manner. Additional supplementary material is provided in the annex. For a visual overview of the structure see Figure 1.3.

2

Multi-sectoral climate change vulnerability assessment for North Rhine-Westphalia*

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. A new framework for the aggregation of vulnerability components is presented, which is often neglected in such assessments. The aggregation across impacts is carried out by two alternative methods, the arithmetic mean and a typological approach via a cluster analysis. 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.

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[*] The first part of this chapter (Section 2.1) and Appendix A have been 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.
This is related to the second part of the chapter (Section 2.2), which has been published as part of the following book chapters: Holsten A., Walther C., Roithmeier O., Kropp J.P.: Integrated Assessment of Vulnerability to Climate Change: The case study of North-Rhine Westphalia. In: Schmidt-Thomé P., Greiving S.: European climate vulnerabilities and adaptation: A spatial planning perspective, Wiley, Chichester, 352 p., in press, and Walther C., Holsten A., Kropp J.P.: Identifying a typology of climate change in Europe. In: Schmidt-Thomé P., Greiving S. (eds.): European climate vulnerabilities and adaptation: A spatial planning perspective, Wiley-Blackwell, Chichester, 352 p. (in press).

2.1 An integrated and transferable climate change vulnerability assessment for regional application

2.1.1 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., 2004b; 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 (2001a) 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:

$$\mathrm{V} = f(\mathrm{I}, \mathrm{AC}), \text{ with } \mathrm{I} = f(\mathrm{E}, \mathrm{S}) \tag{2.1}$$

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, 2013). 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., 2011; 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.

2.1.2 Methods and data

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 sensitivity 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. 2.1).

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:

$$\mathrm{E_{norm}} = \mathrm{E_i} / \left|\mathrm{E_{max}}\right| \tag{2.2}$$

For a graphical representation of this procedure, exemplified for changes in heavy precipitation days occurring over municipalities, see Fig. 2.2.

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 ca-

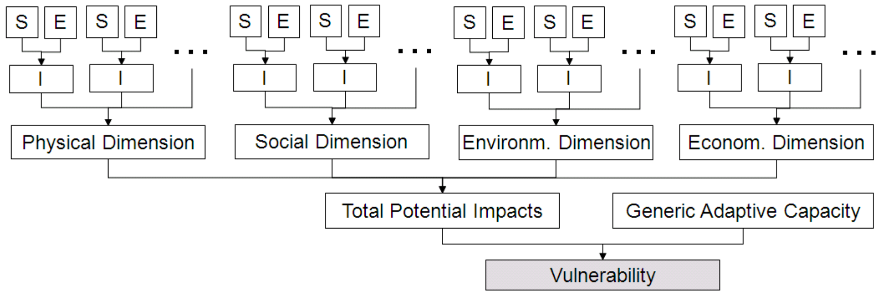

Figure 2.1: Schematic overview over the components and dimensions of the vulnerability analysis. Sensitivity indicators (S) are combined with relevant exposure indicators (E) expressing specific impacts (I). These are aggregated to the physical, social, environmental and economic dimension and to the total potential impacts. Together with the generic adaptive capacity they describe the vulnerability.

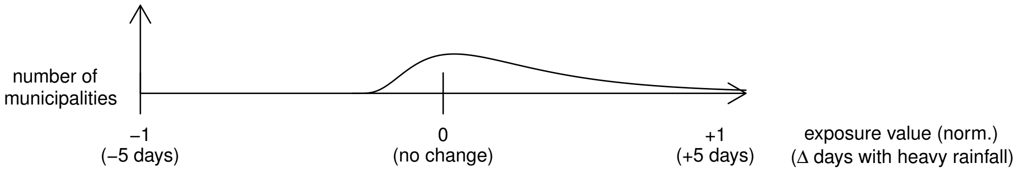

Figure 2.2: Rescaling procedure of exposure variables: Schematic distribution of climatic changes over the municipalities, exemplary for changes in heavy precipitation days. Changes are displayed by their absolute value and their values after rescaling.

pacity 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-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. 2.3, 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., $\mathrm{I_{phys}}$, based on the rescaled sensitivity ($\mathrm{S_{norm,k}}$) and exposure values ($\mathrm{E_{norm,k}}$) for all specific impacts within a dimension (with a maximum number of n):

$$\text{e.g. } \mathrm{I_{phys}} = 1/\mathrm{n} * \sum_{\mathrm{k=1}}^{\mathrm{k=n}} \mathrm{S_{norm,k}} * \mathrm{E_{norm,k}} \tag{2.3}$$

Thus, the aggregation is carried out according to system-specific relationships between the exposure entity and the climatic stimuli (see also Fig. 2.1).

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. $\mathrm{I_{phys}}$ to the total impacts $\mathrm{I_{total}}$. Thereby, weighting factors for the specific dimensions (a to d) can be applied:

$$\mathrm{I_{total}} = (\mathrm{a} * \mathrm{I_{phys}} + \mathrm{b} * \mathrm{I_{soc}} + \mathrm{c} * \mathrm{I_{env}} + \mathrm{d} * \mathrm{I_{econ}})/4 \tag{2.4}$$

Even by including specific impacts with a clear direction according to Fig. 2.3 (right), the subsequent aggregation represents a limitation as it allows for a compensation of impacts across sectors. Yet, we follow this approach to achieve

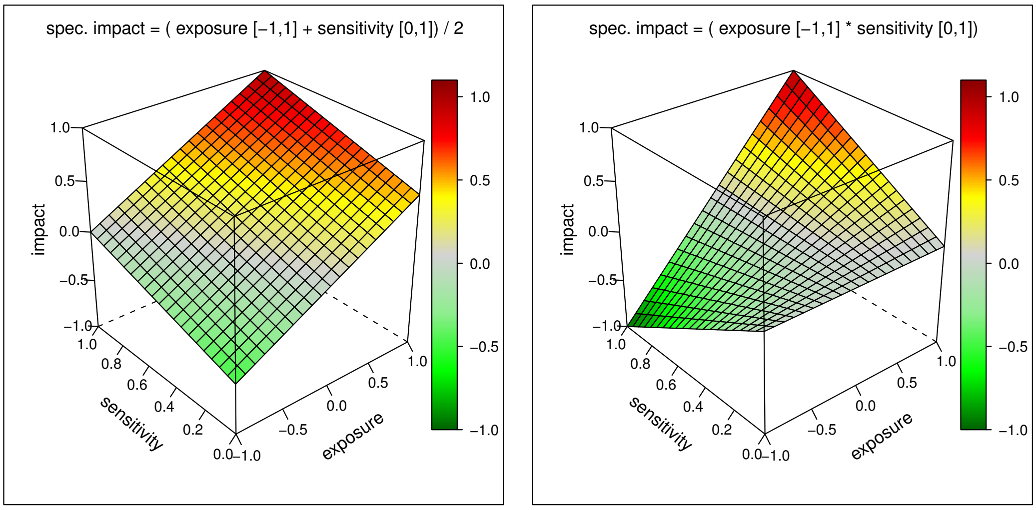

Figure 2.3: Schematic quantification of specific impacts as a function of exposure [-1 to +1] and sensitivity [0 to 1] based on the arithmetic mean (left) or multiplication (right). Resulting impacts values represent adverse (red) or beneficial effects (green). The multiplication process also entails 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.

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. 2.1). 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 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 ”).

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. 2.4). 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.

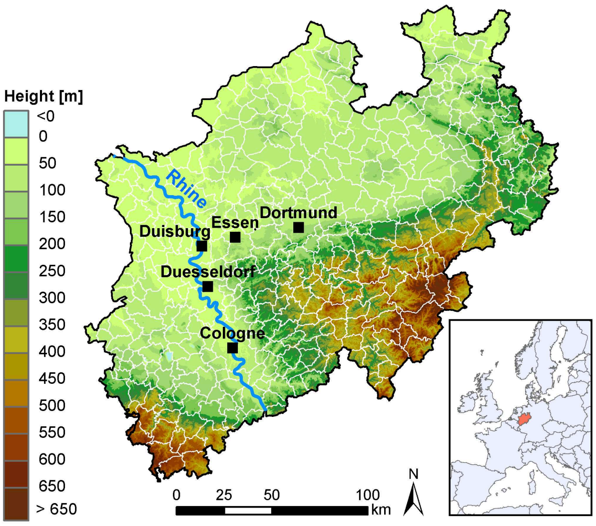

Figure 2.4: The study area North Rhine-Westphalia. Municipalities are delineated by white borders.

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. 2.1 (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., 2009). According to the concept of scales proposed by Fekete et al. (2009), we focus our analysis on the unit of administrative boundaries and the scale of municipalities (LAU2[1], see Fig. 2.4), 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.

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

Table 2.1: 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.2.2. For more information see supplementary material.

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., 2011).
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).

Table 2.1 – *Continued from previous page*

dim.	**exp. unit**	**stimuli**	**relevance**	**methodology**
	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 and Kropp, 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. 2.1 and 2.2) are rescaled based on equation 2.2. 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 ($\mathrm{E}_{\mathrm{i,\,CCLM}}$ and $\mathrm{E}_{\mathrm{i,\,REMO}}$):

$$\begin{aligned} \mathrm{E}_{\mathrm{norm}} &= \mathrm{E}_{\mathrm{i}} / \left| E_{\mathrm{max}} \right| \\ \text{with } \mathrm{E}_{\mathrm{max}} &:= \max\{ \left| \mathrm{E}_{\mathrm{i,\,CCLM}} \right|, \left| \mathrm{E}_{\mathrm{i,\,REMO}} \right| \} \end{aligned} \tag{2.5}$$

Sensitivity values are calculated according to the methodology summarized in Tab. 2.1. 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 2.4 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. (2011a) 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. 2.3 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 2.3: 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

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. 2.2. The applied biophysical and socioeconomic data sources are summa-

Table 2.2: Value ranges of projected changes in the selected climatic variables and corresponding rescaled exposure values.The first line refers to the model CCLM the second line to the model REMO.

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 $\geq 30°C$) [# 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 $\geq 20mm$ [# 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 $\geq 20.5ms^{-1}$ [# days]	3.4 - 6.9 0.14 - 5.6	0.49 - 1 0.02 - 0.66

rized in Tab. 2.4. We prepared the data using the softwares Climate Data Operators (CDO), ArcGIS and R (RDCT, 2009).

2.1.3 Results

The relative exposure differs strongly between the regions in NRW with strongest increases in heat days in the Rhine valley (Fig 2.5). 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 2.6). 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 the mountains and in the Rhine valley for both models (Fig. 2.7, 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. 2.4), 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

Table 2.4: 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 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. 2.8). 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 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. (2011a) 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

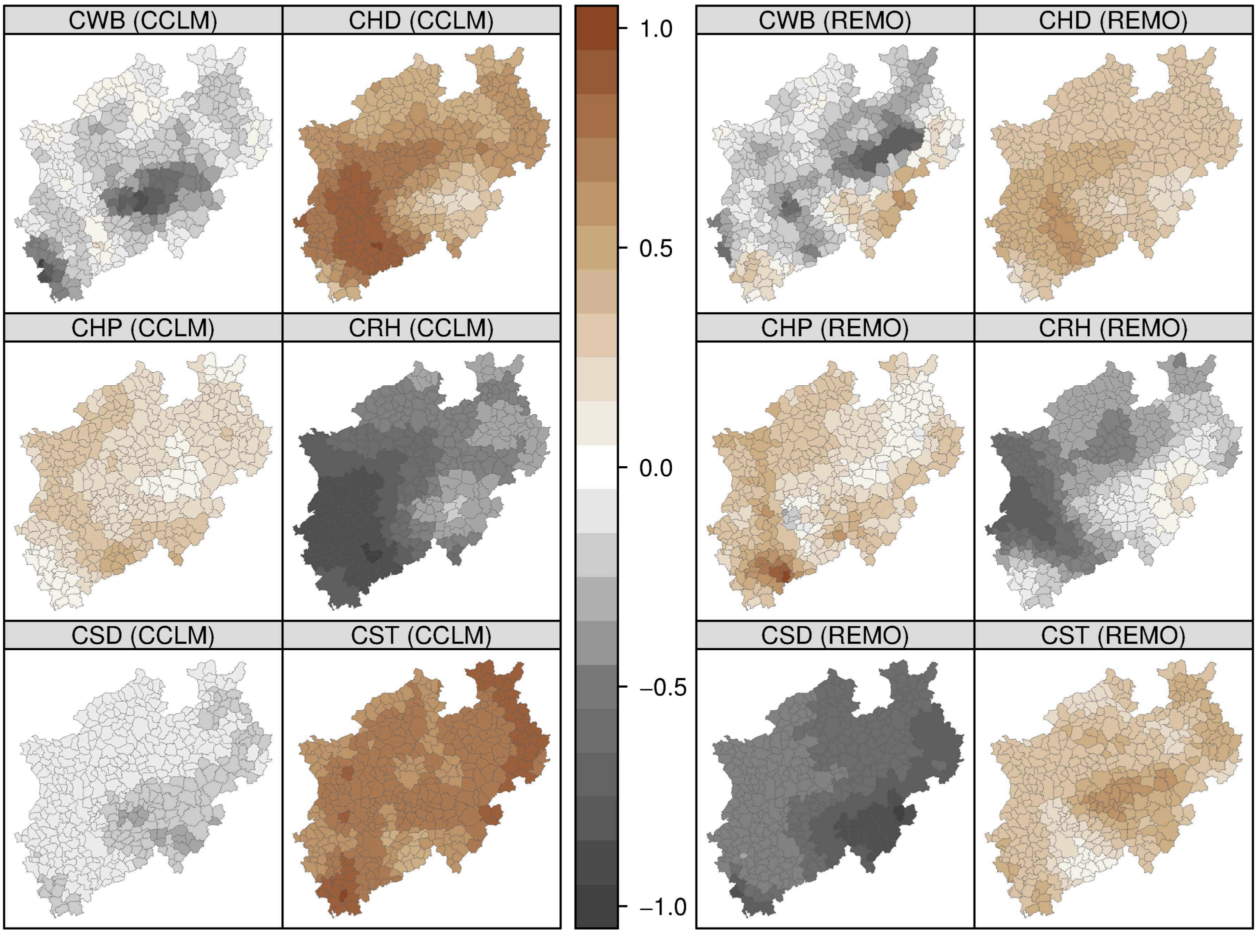

Figure 2.5: Rescaled exposure variables for the models CCLM (left) and REMO (right). Values are scaled to the data space of NRW for both models, ranging from -1 (decreases) to 1 (increases). The exposure is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B. For abbreviations see Tab. 2.2

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. 2.9). 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.

2.1.4 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

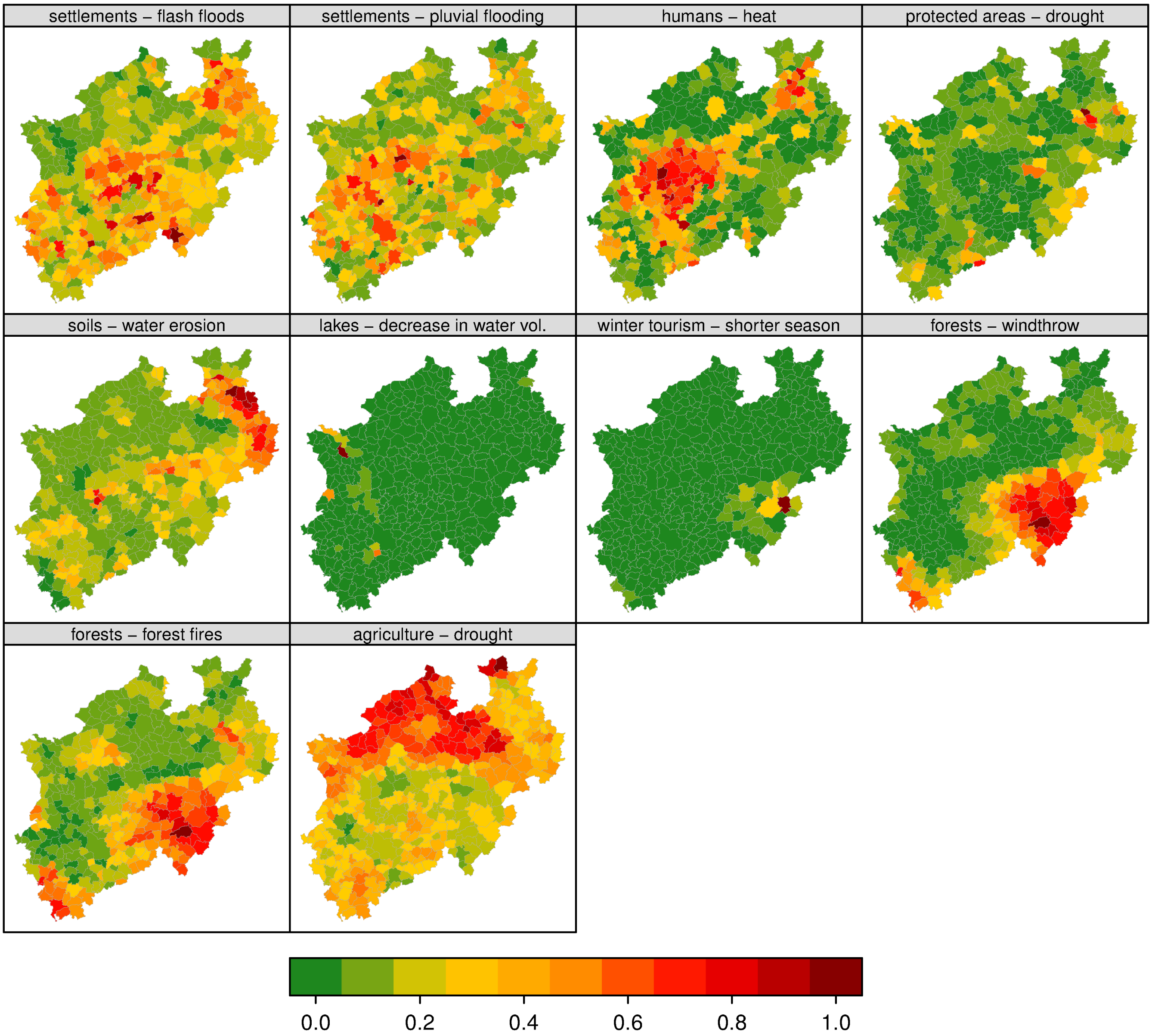

Figure 2.6: Sensitivity values ranging from 0 (low) to 1 (high). Values are scaled to the data space of municipalities in NRW.

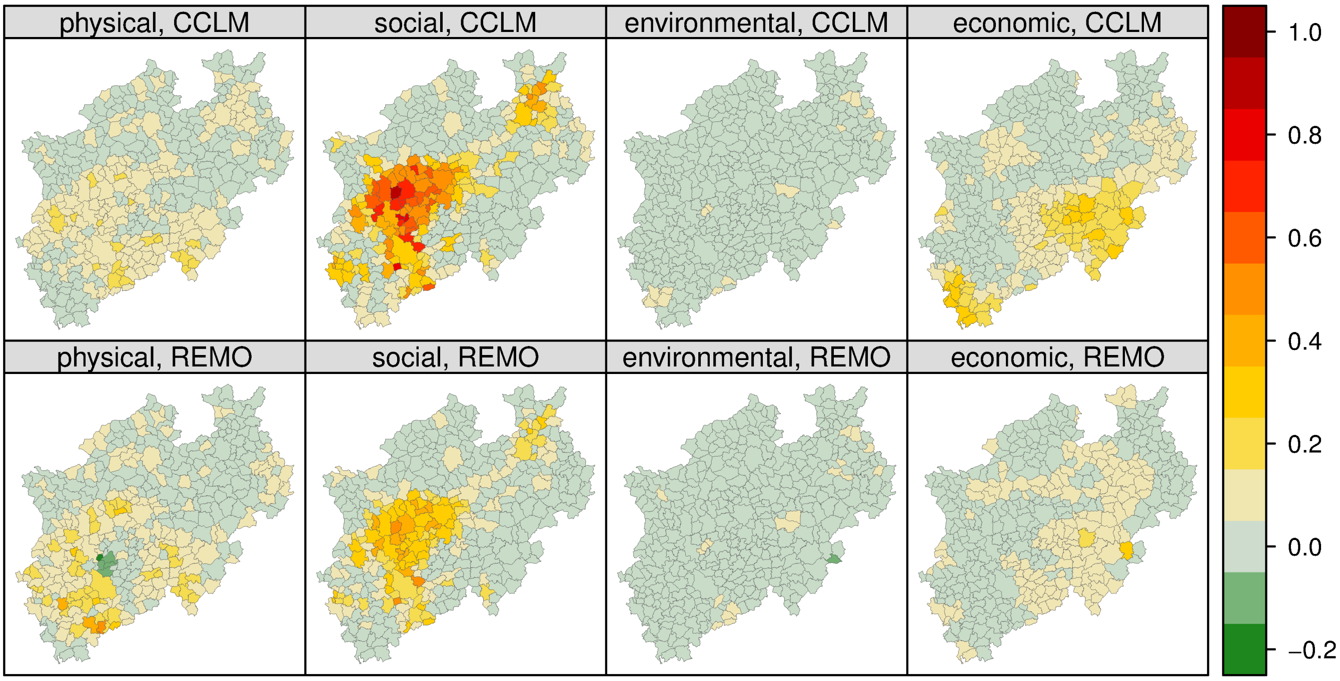

Figure 2.7: Aggregated potential impacts based on the climate models CCLM (top) and REMO (bottom) for the physical, social, environmental and economic dimension. Values from 0-1 represent adverse impacts, below 0 beneficial impacts. Underlying exposure and sensitivity variables have been scaled to the data space of both models. Exposure is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B.

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, 2013). 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 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

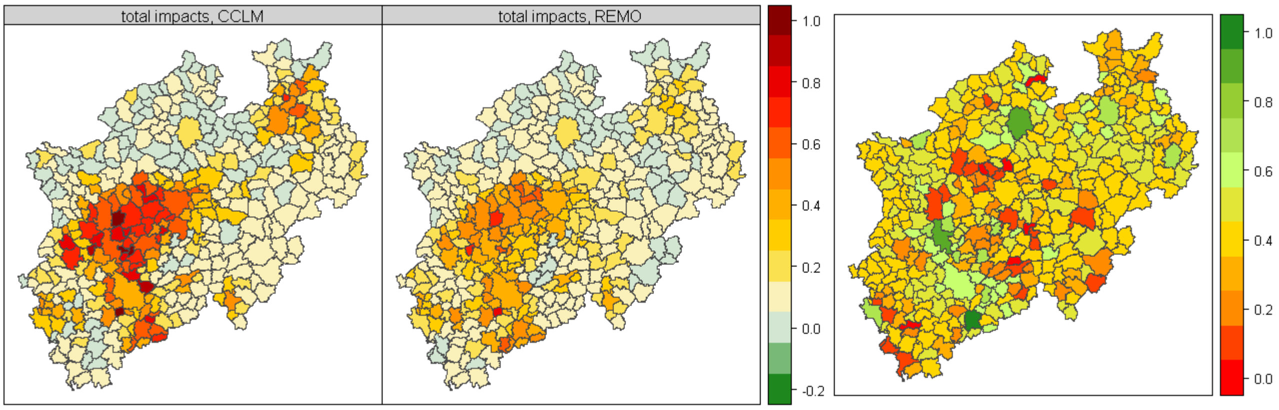

Figure 2.8: Total potential impacts (left) based on the climate models CCLM and REMO, considering equal weighting factors for the dimensions, and generic adaptive capacity (right). Impact values from 0-1 represent negative impacts, below 0 positive impacts. Values of adaptive capacity range from 0=low 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.

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., 2009). 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 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

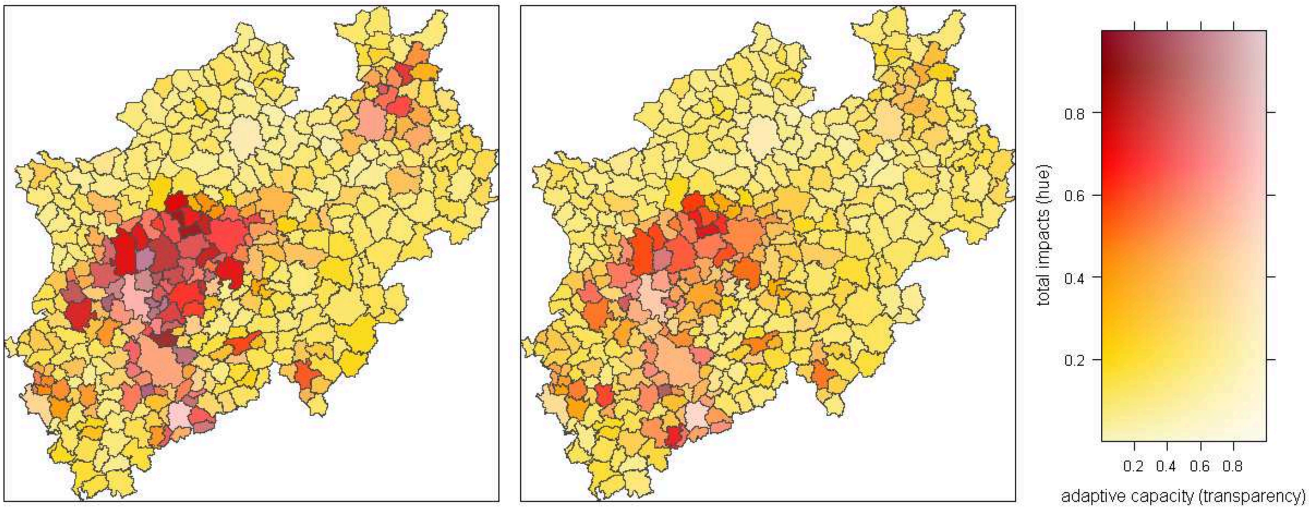

Figure 2.9: Visualization of vulnerability based on aggregated impacts and the generic adaptive capacity for CCLM (left) and REMO (right). A high adaptive capacity reduces negative impacts (hue from yellow to red), which is visualized by changes in the level of transparency. For the aggregation of the 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.

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. 2.5.

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 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

Table 2.5: 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	

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.

2.1.5 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.

2.2 Typological categorization of impacts as an alternative aggregation approach in a multi-sectoral vulnerability assessment

This section follows up on the previous multi-sectoral vulnerability analysis and presents an alternative approach for the aggregation of sector-specific impacts: a typological categorization via a cluster analysis.

The above presented approach of aggregating impacts via arithmetic mean over all sectors aims at quantifying the full impact burden of regions. However, even by including specific impacts with a clear direction according to the method outlines in Figure 2.3a, the subsequent aggregation represents a limitation as it allows for a compensation of impacts across sectors. Therefore we alternatively follow an approach of identifying regions of similar impact burden based on the calculated sector-specific impacts. These typologies of climate change impacts are developed by means of a cluster analysis, based on the specific indicators values calculated for all municipalities. This allows to categorize a data set by grouping the objects into different clusters, according to their similarities. The cluster mechanisms can be distinguished in hierarchical, partitioning and density-based methods (Handl et al., 2005). Our analysis is mainly based on the second method, i.e. K-means (Mac Queen, 1967; Hartigan and Wong, 1979), which minimizes the total within-cluster sum-of-squares (Steinley, 2006). We further use the hierarchical clustering to initialize the partitioning method, as shown by Peterson et al. (2010) to be a valid method for initialization. This clustering approach has been applied as described in Sietz et al. (2011).

The major advantage of the K-means method is the high calculation speed. However, there is a risk of local minima in the optimization process and the user has to choose in advance the expected number of clusters. To overcome this, we introduce a method to find an appropriate number of clusters based on the following criteria: the variance ratio (ratio between-cluster variance and the inner-cluster variance, see Calinski and Harabasz (1974)), the consistency measure (the extent of overlap of the clusters between two K-Means runs for a pre-given cluster number, see Sietz et al. (2011)) and the silhouette-width (measure for how much the elements belong to the assigned cluster, see Kaufman and Rousseeuw (1990)). Each calculation is based on 200 loops. Higher values of these measures indicate a better representation of the data regarding the respective number or clusters.

The cluster analysis is carried out for the sector-specific impacts of each municipality based on climate data of the CCLM and REMO model (Figure A.1), which were rescaled between 0 and 1 prior to the calculations based on the minimum and maximum values of the dataset. The results show that the variance ratio criteria and the silhouette index point to three clusters (Fig. 2.10 a-d) . This number is also represented by a local maxima regarding the consistency measure for the CCLM model (Fig. 2.10 e). The median consistency measure based on results of the REMO model indicates an optimal number of four clusters, however, with a very small deviation to the three cluster option (Fig. 2.10 f). Also for the latter the median value is higher. In order to compare our results, we therefore chose to represent our impact results based on three clusters for both climate models.

These clusters are characterized by different combinations of the sector-specific impacts (Fig. 2.11) and different spatial distributions within the state NRW (Fig. 2.12). For both models, the first cluster (brown color) shows a strong impact regarding storm causing windthrow in forests especially in the mountainous regions of NRW. These include the Sauerland and Eifel mountains as well as parts of the Egge mountains in the East. The second cluster is especially marked by a high social impact regarding heat waves and is located in the Rhine valley and metropolitan region. Also the region around the city of Bielefeld is assigned to this cluster. The third cluster is characterized by a more balanced pattern of impacts, with relatively lower values regarding heat impacts and impacts on forest but higher values regarding environmental and agricultural impacts. This clus-

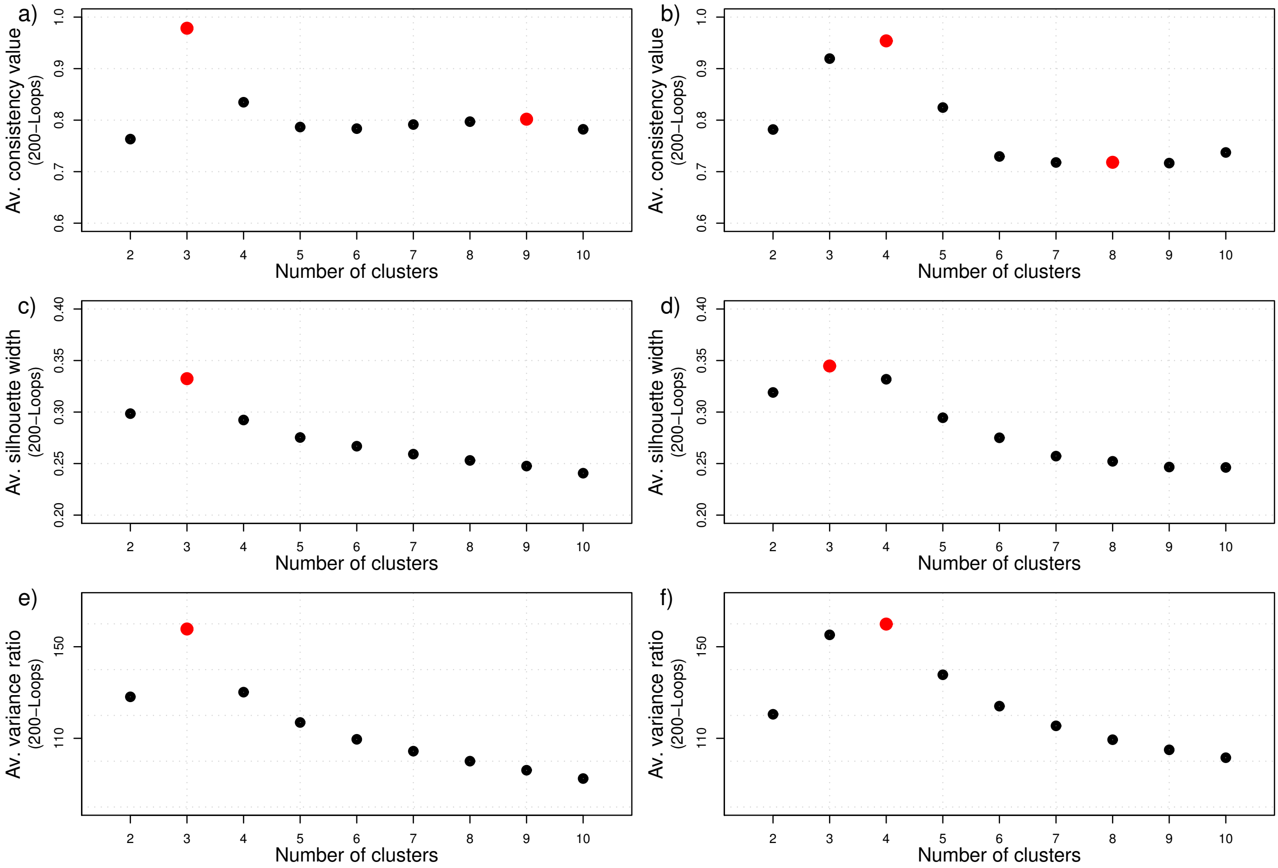

Figure 2.10: Consistency measure (a,b) , ratio of the between-cluster variance and the inner-cluster variance (c,d) and silhouette width (e,f) for cluster numbers 2-15 based on the model CCLM (left) and REMO (right). The values represent averages for 200 repetitions of the cluster-specific measures. Local maxima regarding the optimal number of clusters are marked by red points.

ter is more dominant in the low lying Westphalian Bay and the foothills of the mountains. A slightly higher number of municipalities is allocated to cluster 1 according to the CCLM model compared to the REMO model. However, overall, the identified clusters are quite robust regarding the chosen climate model.

When comparing the pattern of these clusters to the adaptive capacity of the municipalities (see Fig. 2.8, right), a spatial overlap is not directly apparent. Rather the adaptive capacity varies strongly between municipalities. However, the upper Rhine region including Bonn, Cologne or Düsseldorf as well as the city of Bielefeld in the Northeast exhibit higher adaptive capacities. At the same time, they are all located within the second cluster, which is marked by high social impacts. Yet, the remaining area of this cluster, mainly the Ruhr region show a low adaptive capacity. Low values of adaptive capacity are also found for several municipalities belonging to the first cluster of the mountainous regions, characterized by stronger impacts regarding the forestry sector. The third cluster, located in the region of Münsterland and parts of the Bay of Cologne show by and large a medium level of adaptive capacity, with the exception of the city of Münster.

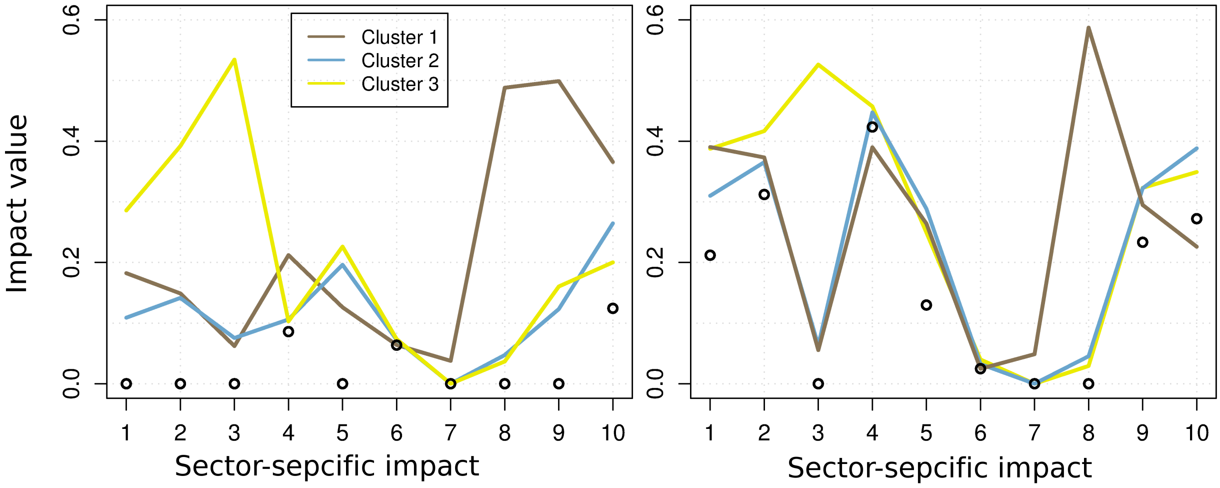

Figure 2.11: Values for the identified cluster centers regarding the ten sector-specific impacts in NRW, according to the model CCLM (left) and REMO (right). The colors of the clusters are identical to those used in Fig. 2.12. Note that for the cluster analysis, each input variable was rescaled between 0 and 1, original impact values of zero are marked by black circles (e.g., for all clusters an increase in vulnerability to heat is apparent). Indicators are numbered according to the impacts described for their exposure unit in Tab. 2.1: 1= settlements - flash floods, 2 = settlements - pluvial flooding, 3= humans - heat, 4 = protected areas - drought, 5 = soils - water erosion, 6 = lakes - decrease in water volume, 7 = winter tourism - shortening of season, 8 = forests - windthrow, 9 = forests - forest fires, 10 = agriculture - drought. The underlying exposure is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B.

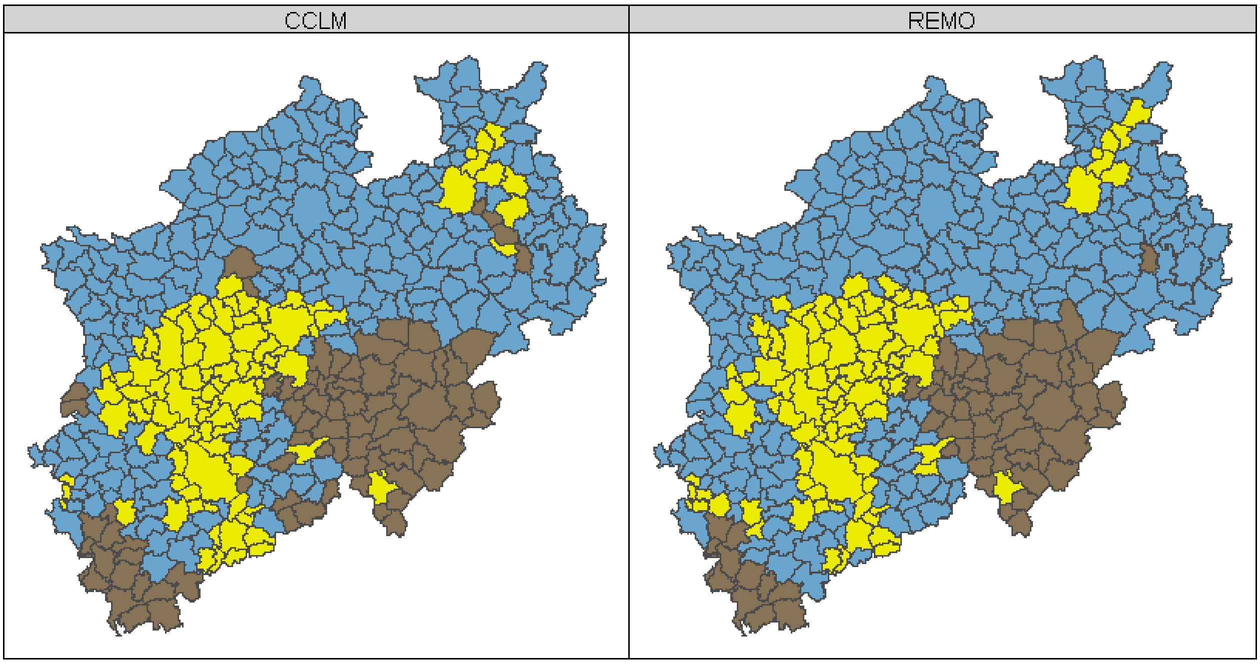

Figure 2.12: Spatial distribution of the three identified clusters based on the model CCLM (left) and REMO (right). The cluster colors are identical to those used in Fig. 2.11. The underlying exposure is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B.

3

Climate change impact assessment for the forestry sector in North Rhine-Westphalia[*]

Abstract

Storms have a high potential to cause severe ecological and economic losses in forests. We performed a logistic regression analysis to create a storm damage sensitivity index for North Rhine-Westphalia, Germany, based on damage data of the storm event “Kyrill”. Future storm conditions were derived from two regional climate models. We combined these measures to an impact metric, which is embedded in a broader vulnerability framework and quantifies the impacts of winter storms under climate change until 2060. Sensitivity of forest stands to windthrow was mainly driven by a high proportion of coniferous trees, a complex orography and poor quality soils. Both climate models simulated an increase in the frequency of severe storms, whereby differences between regions and models were substantial. Potential impacts will increase although they will vary among regions with the highest impacts in the mountainous regions. Our results emphasise the need for combining storm damage sensitivity with climate change signals in order to develop forest protection measures.

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3.1 Introduction

Storms are known to be the most devastating natural disasters in the world with regard to their spatial extent, frequency of occurrence and insured damages (Rauch, 2005), and to be the most important natural stressors for forests (Schelhaas et al., 2003). In Germany, 75% of economic losses related to natural disasters from 1970 to 1998 can be attributed to storms, mostly frontal depressions occurring in winter (MunichRe, 1999).

Methodologies applied for investigating past storm activity differ as regards how cyclones are identified, tracked and quantified (Raible et al., 2008; Ulbrich et al., 2009). While no significant long-term trend in the geostrophic wind strength has been found in Central Europe, decadal variations with maxima in the early and late 20th century were identified (Matulla et al., 2008). Stronger storms were observed in the mid 1970s and at the beginning of the 1990s in Duesseldorf, in the German Federal State of North Rhine-Westphalia (NRW) (Kasperski, 2002), with an increase of the annual number of days with gusts ≥8 Bft by 40% from 1969 to 1999 (Rauch, 2005).

A clear increase in storm-damaged timber has been recorded in Central Europe in the 20th century (Schelhaas et al., 2003; Usbeck et al., 2010). This trend is not only caused by stronger storms (Usbeck et al., 2010) but also by human impacts on forests and soils, by increased growing stock and forest area and enhanced awareness regarding storm damage (Schelhaas et al., 2003; Nilsson et al., 2004).

As the cause of the highest insured losses since at least 1990, Kyrill ranks among the most devastating storms of the last decades in Central Europe (MunichRe, 2007). One third of the European and half of the German forest loss was recorded in NRW (MUNLV, 2010), which was hit by Kyrill on 18th January 2007, with long lasting hurricane-force winds over a large corridor (Fink et al., 2009).

Various studies which statistically analysed the present storm activity for Germany have assigned a high storm exposure to summits in mountain ranges (Kasperski, 2002; Hofherr and Kunz, 2010). Future cyclone activity is expected to change under global warming conditions, whereby its regional effects will be highly variable (Bengtsson et al., 2006; Ulbrich et al., 2009). A multi-model ensemble indicated an increase in the number of severe northern hemisphere cyclone events until 2050 (Lambert and Fyfe, 2006), and storm intensities were projected to increase in Northern and decrease in Southern Europe until the end of the 21st century (Bengtsson et al., 2006). The number of the most intense cyclones in Western Europe is expected to rise until 2100 (Pinto et al., 2007; Rockel and Woth, 2007). In this context, the regional climate model CCLM simulated the annual number of days with gusts ≥8 Bft to increase by up to 20% in Central Europe in 2071-2100 compared to 1961-1990 (Rockel and Woth, 2007). Pinto et al. (2010) showed similar trends in winter storm impacts in NRW using a mesoscale model with boundary conditions of a general circulation model.

A dynamic exposure is hardly considered in studies related to storm damages in forests, which generally assume a constant wind regime. Straightforward approaches include expert systems deriving general rules from local experience and literature reviews (Rottmann, 1986; Mitchell, 1998). Alternative concepts apply wind damage indices derived from post-event analyses (Schmidtke and Scherrer, 1997; Schmoeckel and Kottmeier, 2008) or modelling approaches ranging from widely used regression models (Jalkanen and Mattila, 2000; Schütz et al., 2006; Schindler et al., 2009; Nakajima et al., 2009), classification trees (Dobbertin, 2002) and neural networks (Hanewinkel et al., 2004) to mechanistic models (Ancelin et al., 2004; Peltola et al., 1999; Gardiner et al., 1999; Panferov et al., 2009).

Climate change impact assessments have become common in many disciplines (Füssel and Klein, 2006). However, only few studies have investigated windthrow impacts under climate change by considering altering wind speeds and changes in forest productivity (Blennow et al., 2010) or soil moisture regime (Panferov et al., 2009). Furthermore, the effects of changing periods of soil frost Peltola et al. and changing tree species composition Peltola et al. on root anchorage and critical wind speeds and thus on storm damage prob-

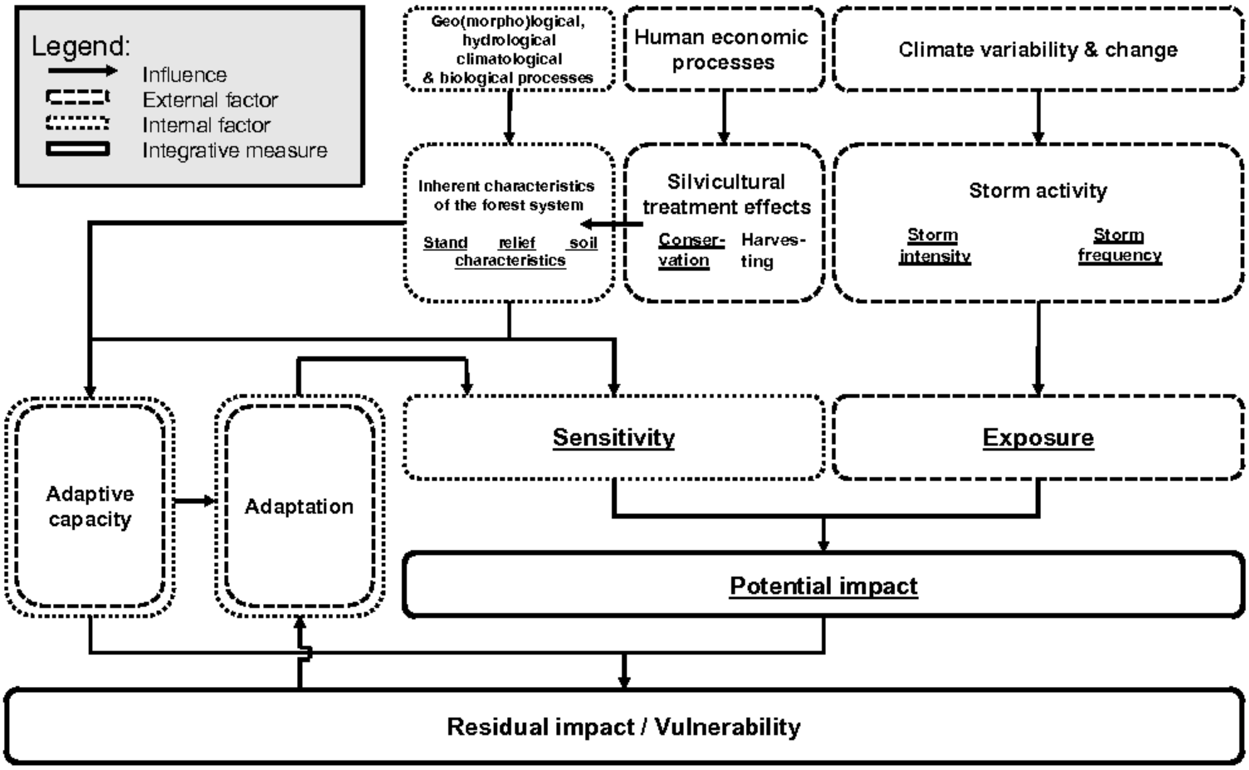

Figure 3.1: Framework for the assessment of windthrow impacts on forest stands under climate change. Factors considered in the study are underlined.

abilities have been studied.

Influential factors affecting windthrow as measures of forest sensitivity to wind damage were identified by Kropp et al. (2009) and combined with future storm conditions for NRW. However, variables included in their spatially highly resolved multivariate sensitivity index were chosen arbitrarily and the storm climate was derived from a single climate model using a universal threshold value of wind speed. We improved this index to develop a sound, comprehensible and coherent storm impact measure considering forest, relief and soil characteristics as well as the influence of storms under changing climatic conditions. Thereby, we addressed the following questions:

1. What are the controlling factors associated with storm damage in NRW and which spatial patterns of sensitivity result from their interaction?
2. How will storm frequency change in NRW until 2060?
3. What is the resulting potential impact of winter storms on forests in NRW under a changing climate?

3.2 Material and Methods

3.2.1 Vulnerability framework for storm damages in forests

Vulnerability is commonly conceived as the degree of susceptibility of a system and its components to suffer harm from the exposure to certain stressors (Turner et al., 2003). We based our terminology on the vulnerability concept of the IPCC (2007) with the components exposure, sensitivity and adaptive capacity. Sensitivity is the dimension to which a system (forest) responds to an external stimulus (wind speed). The extent of the latter is described by the exposure. Impacts characterise the effects of climate change (windthrow, which we define in the following by both uprooting and stem breakage) on an exposure unit. While the capability to plan and execute adjustments to climate stimuli is termed adaptive capacity, adaptation characterises con-

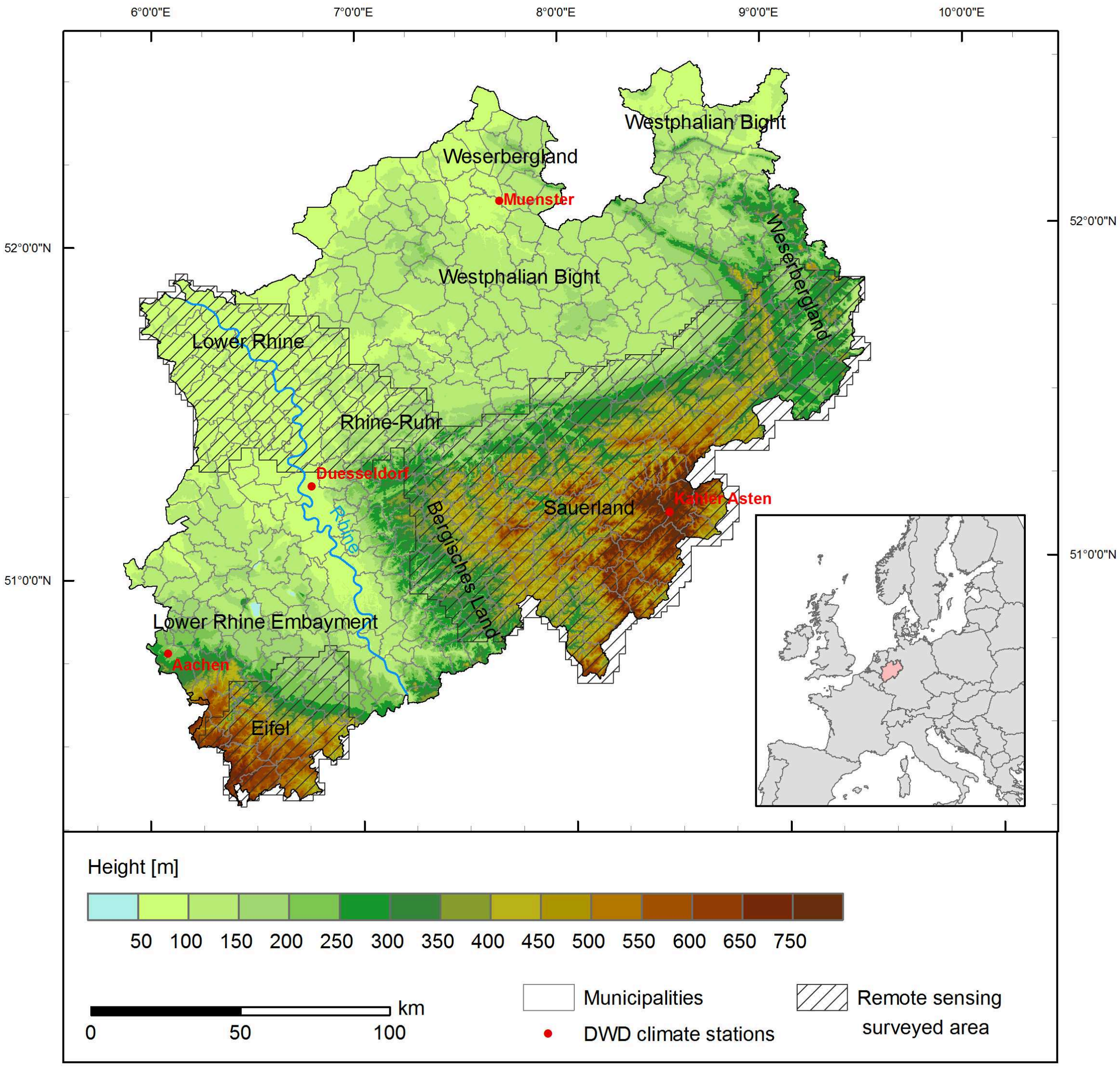

Figure 3.2: The study region North Rhine-Westphalia, its location within Europe, the sites of analysed climate stations and the area subjected to aerial damage investigations of windthrow.

crete measures to reduce the sensitivity of a system (IPCC, 2007). When these components are taken into account, the resulting residual impacts are examined. Otherwise, the potential impacts are the focus of this research.

These dimensions of vulnerability result in a working scheme (Fig. 3.1) based on the climate impact assessment frameworks presented by Füssel and Klein (2006) and Ionescu et al. (2008). Vulnerability of forests to storms is affected by inherent characteristics of the forest system and exogenous drivers. The former include biological (e.g. stand characteristics like species composition, age, height and root structure), pedological (e.g. substrate, acidity and soil moisture influencing rooting and vitality characteristics) and topographical factors (e.g. slope and altitude modifying the local wind climate) (Rottmann, 1986; Ruel, 1995; Aldinger et al., 1996; Mitchell, 1998). The exposure is determined by the magnitude and frequency of storms driven by climate variability and change. The anthropogenic adaptive capacity of the local forestry enterprise comprises the forester's knowledge and activity. Adaptive capacity can be also regarded as the ability of the forest system to adjust to a changing storm climate. We assume adaptive capacity to be constant over space and sensitivity to stay constant over time. However, biological factors such as tree species composition could be modified by changing climate conditions and altering silvicultural strategies.

Influential factors included in this study are underlined in Fig. 3.1. Thus, we calculated the potential windthrow impact on forests in NRW, considering their sensitivity and exposure to storms.

3.2.2 Study area

Located in the northwest of Germany (Fig. 3.2), NRW has 0.9 mil. ha (26%) of forest area of which 3% were damaged by Kyrill (MUNLV, 2010). Deciduous trees cover 52% and coniferous trees 48% of the total forest area. Whereas the former are concentrated in the lowlands, the latter are prevalent in the mountain ranges Eifel, Weserbergland and Sauerland (highest point: Kahler Asten 839 m.a.s.l.). Predominant tree species are European beech (*Fagus sylvatica*), Pedunculate oak (*Quercus robur*), Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*).

Forestry generated 7.2% of the gross domestic product of NRW in 2001 (Schulte, 2003). In addition to these economic benefits, forests are of great importance for the ecological balance in densely populated areas of this state (MUNLV, 2010). Thus, storms have a high potential to cause severe economic and ecological losses in NRW.

3.2.3 Data

To evaluate the significance of variables for storm damage sensitivity, we used windthrow data from the cyclone Kyrill derived from aerial photograph data from 2007 covering the main damaged areas Sauerland, Eifel and Lower Rhine, which account for 35% of NRW (Fig. 3.2). Minimum detection size of the damaged area was limited to 0.25 ha and to damage to over half of the area (State Office for Forestry NRW). The mean area of the damaged sites amounted to 2 ha with a maximum of 212 ha. The damages were caused by wind gusts of around 30-40 $m\ s^{-1}$ in NRW (DWD, 2010).

Sensitivity variables to explain this spatial pattern of storm damage were selected according to the scheme presented in Fig. 3.1 and are listed in Table 3.1. However, spatially continuous data on this fine scale is scarce. A regional soil map (1:50 000) was available from the Geological Survey NRW, providing information on soil type and structure. A regional digital elevation model (DEM, 50 m, State Office for Nature, Environment and Consumer Protection (LANUV)) was applied to provide data on relief characteristics. Spatially continuous data on forest structure (e.g. stand height and age) were not available for the whole region. Therefore, we concentrated on the forest type using highly resolved data from the Authoritative Topographic-Cartographic Information System (ATKIS®, State Office for Ecology, Soil and Forestry NRW (LÖBF)) with a scale of 1:25 000. To account for silvicultural treatment effects, we included data on natural forest reserves, which have not been subjected to anthropogenic impacts for decades (State Office for Forestry NRW). Since only coordinates and information on the area of these sites were available, we digitalised their spatial extent assuming a circular shape of the area around their centres. In addition, we obtained measured daily maximum wind speed at 10 m height from 1991 to 2009 for four climate stations (Aachen, Duesseldorf, Kahler Asten, Muenster, see Fig. 3.2) from the German Weather Service (DWD, 2010). Simulated daily maximum wind speed at 10 m height was derived from the regional climate model REMO (Jacob et al., 2006), a hydrostatic dynamical model and CCLM (model version 2.4.11), a non-hydrostatic dynamical model (Lautenschlager et al., 2009). Spatial resolution amounts to 0.1° for REMO and 0.2° for CCLM. All available runs covering the period from 1960-2100 under scenario A1B (Nakicenovic et al., 2000) were averaged. According to these models, temperature over NRW will increase by $1.3-1.9°$ until 2060 or $3-3.3°$ until 2100 compared to 1961-1990 under scenario A1B. Rainfall will increase by 5-7% until 2060 or 1-6% until 2100 (Meinke et al., 2010).

3.2.4 Methods of the sensitivity analysis

Prior to the sensitivity analysis, we transformed data on storm damage, land use and soil (Table 3.1) to a common 50 m grid overlaying exactly with the DEM grid, based on the maximum area in each cell. Cells damaged by Kyrill (KYR) and cells under natural

Table 3.1: Summarised variables used in the regression model with regard to their data type, units and minimum and maximum values in the study area.

Code	Description	Type	Units	Min	Max
DIS	Distance to forest edge	Continuous	m	7	1734
DEC	Deciduous forest	Binary	-	0	1
MIS	Mixed forest	Binary	-	0	1
CON	Coniferous forest	Binary	-	0	1
NFR	Natural forest reserve	Binary	-	0	1
SLO	Slope	Continuous	°	0.0	47.0
HIL	Hillshade	Continuous	-	0.0	167.0
ALT	Altitude	Continuous	m	9.5	838.1
CUR	Curvature	Continuous	10^{-2} *z-unit*	-4.04	4.71
NSL	Northern slope	Binary	-	0	1
ESL	Eastern slope	Binary	-	0	1
SSL	Southern slope	Binary	-	0	1
WSL	Western slope	Binary	-	0	1
CAP	Capillary action	Continuous	$mm\ d^{-1}$	0	6
ICA	Infiltration capacity	Ordinal	-	1	4
FCP	Field capacity	Continuous	mm	10	625
AFP	Air-filled porosity	Continuous	mm	2	220
AWC	Available water capacity	Continuous	mm	7	438
WPM	Water permeability	Continuous	$cm\ d^{-1}$	2	500
CEC	Cation exchange capacity	Continuous	$mol\ m^{-2}$	2	1892
DGT	Depth to the goundwater table	Continuous	dm	1	29
SML	Soil moisture level	Ordinal	-	1	14
ERO	Soil erodibility	Continuous	$(th)(haN)^{-1}$	0.01	0.60
SQT	Soil quality	Ordinal	-	10	80
GSZ	Grain size	Ordinal	-	1	9
KYR	Area damaged by Kyrill	Binary	-	0	1

forest reserve (NFR) were given binary coding. We also coded cells according to forest types by means of the dummy variables “coniferous” (CON),“deciduous” (DEC) and “mixed” (MIX). As an additional variable, we calculated the Euclidean distance to the next forest edge for each grid cell (DIS).

Slope (SLO), curvature (CUR), hillshade (HIL) and orientation were calculated from the DEM. Orientation was converted into four dummy variables (East (ESL), South (SSL), West (WSL), North (NSL)). Hillshade is defined by the potential illumination of a surface according to specified location parameters of the light source. To simulate the exposition to westerly winds, this source was set to an azimuth of 270°and an altitude of o°, as these values best represent the synoptic situation of Kyrill (Fink et al., 2009). Hillshade has an integer value range of 0 (fully sheltered site) to 255 (fully exposed site). Soil parameters provided by the applied soil map included capillary action (CAP), infiltration capacity[1] (ICA), field capacity (FCP), air-filled porosity (AFP), available water capacity (AWC), water permeability (WPM), cation exchange capacity (CEC), depth to the goundwater table (DGT), soil moisture level[2] (SML), erodibility (ERO), grain size[3] (GSZ) and soil quality (SQT), a national soil rating, integrating grain size, parent rock and development stage of the soil on a linear

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[1] Values of ICA (denominated suitability for decentralised seepage in the soil map) consider the depth of unconsolidated rock, influence of groundwater or water logging and the permeability of the upper 2 m of the soil. The four available classes from low to high infiltration capacity are characterised by 1, strong influence of water logging; 2, permeability below 43 $cm\ d^{-1}$ without water logging or 43-86 $cm\ d^{-1}$ with medium water logging; 3, permeability of 43-86 $cm\ d^{-1}$ or above 86 $cm\ d^{-1}$ with medium water logging; 4, permeability above 86 $cm\ d^{-1}$ without water logging.

[2] 14 classes: 1, very dry; 2, dry; 3, moderately dry; 4, fresh; 5, very fresh; 6, alternating (dry>moist); 7, alternating (dry≤moist); 8, alternating (fresh>moist); 9, alternating (fresh≤moist); 10, waterlogged; 11, moderately gleyic; 12, gleyic; 13, moist; 14, wet.

[3] Ten classes: 1, organic; 2, clayey silt; 3, clayey loam; 4, loamy clay; 5, heavy loamy sand; 6, loamy sand; 7, sandy silt; 8, sandy loam; 9, sand; 10, coarse grained.

0-100 scale increasing with improving conditions for plant growth (AG Boden, 2005). We omitted grid cells with missing values for any of the variables from further processing. Thus, a total of 3.3 mil. cells was available of which 2.3 mil. cells lay within the area subjected to aerial damage investigations.

We randomly selected two mutually exclusive samples (S1, S2) comprising 460 000 grid cells each (20% of the total) located inside the area detected for storm damage, using the Hawths Tools extension for ArcGIS (Beyer, 2004). To investigate potential differences in characteristics of damaged areas and their immediate surroundings, we selected a third sample (S3) from the same 50 m grid containing all 108 000 damaged cells and the same number of cells randomly selected from a circular buffer area around these sites.

We then studied the extracted attributes (see Table 3.1) regarding their influence on storm damage using logistic regression analysis as it is well suited to predict the probability of occurrence of a dichotomous outcome (Peng et al., 2002) and has been well established in earlier wind disturbance studies (Jalkanen and Mattila, 2000; Schütz et al., 2006; Schindler et al., 2009; Nakajima et al., 2009). The scale level of predictors of the logistic regression model (logit model) was at least interval or dichotomous. Moreover, the sample size was satisfactory since it includes 25 000 *damaged* cells out of 460 000 cells (S1, S2) or 108 000 out of 216 000 (S3) cells. As a further precondition, residuals have to be distributed binomially. This can be expected as far as sampling is made randomly (Peng et al., 2002). However, the absence of multicollinearity, heteroscedasticity and the linearity between the logit transformed regress and and the regressors are further requirements which we cannot guarantee within this study.

In order to reduce model complexity and multicollinearity, capillary action, field capacity, air-filled porosity and water permeability were excluded, since they showed a correlation of $R > 0.7$ with soil moisture level, cation exchange capacity, depth to groundwater table or grain size, respectively. We then fitted the model to the data for both samples by using backward variable selection and applying the glm-command of the statistical software R (RDCT, 2009) based on the following equation (Pampel, 2000):

$$ln\left(\frac{p}{1-p}\right) = \beta_0 + \sum_{i=1}^{n} \beta_i \; x_i \qquad (3.1)$$

where n is the number of predictors, p is the probability of a cell to be *damaged* over half of its area, β_0 is the intercept, x_i are the predictor values and β_i are the parameters derived by maximum likelihood estimation. Starting with a complete model, predictors were removed one by one in case of meeting Akaike's information criterion (AIC, Akaike, 1998). AIC indicates the goodness of fit by means of the log-likelihood value and prefers models with less parameters against models with more parameters. Parameter elimination was continued until the removal of the next variable would decrease the log likelihood such that the AIC value would increase again.

We tested the significance of β_i using the Wald-Test, which verifies the hypothesis that β_i=0 by comparing the ratio of β_i to its estimated standard error with the z-value of a standard normal distribution (Hosmer and Lemeshow, 1989). The weight with which each independent variable influences the dependent variable was derived from standardised parameters β_i^*, which we calculated as follows (Pampel, 2000):

$$\beta_i^* = \beta_i \; \frac{s(x_i)}{s(y)} \qquad (3.2)$$

where $s(x_i)$ is the standard deviation of the predictors X_i and $s(y)$ the standard deviation of the outcome variable.

The term $ln\left(p\;(1-p)^{-1}\right)$ in formula (3.1) is called the logged odds (logit) where the odds of an event are defined as the probability of its occurrence, divided by the probability of its non-occurrence. In this context, β_i (β_i^*) point out how the logged odds respond if the independent variable changes by one unit (one standard deviation) and all others are held constant. Additionally, odds ratios $\Psi = exp(\beta_i)$ were calculated. In terms of dichotomous variables, Ψ determines how many times storm damage is more likely to occur for a given binary characteristic compared to its opposite (Hosmer and Lemeshow, 1989). Applied to continuous variables, the difference of Ψ from 1 exhibits the change in the odds for a one-unit change in the predictor variable (Pampel, 2000).

Peng et al. (2002) recommend a multitude of methods to evaluate the logit model of which a selection were calculated for this study, including the goodness of fit indicator D^2 (ratio of residual deviance to null deviance) and some of its derivatives by using the R-Package *descr* (Aquino et al., 2009). We determined model fits separately for each of the three samples and applied the fitted model with the highest D^2 to the whole storage record to calculate the storm damage probability as follows (Hosmer and Lemeshow, 1989):

$$p = \frac{exp(\beta_0 + \sum_{i=1}^{n} \beta_i \; x_i)}{1 + exp(\beta_0 + \sum_{i=1}^{n} \beta_i \; x_i)} \tag{3.3}$$

In order to evaluate the power of the model to reproduce the area damaged by Kyrill, we transformed p ranging from 0 to 1 to a binary number by defining a threshold t from which onwards a certain cell is coded *damaged* and otherwise *undamaged*. We then calculated the true positive rate, true negative rate and overall model accuracy. The true positive rate is defined as the percentage of correctly classified *damaged* cells. The true negative rate and overall model accuracy are similarly defined terms, whereas the first is related to *undamaged* cells and the second is related to all cells regardless of being *damaged* or not. We visualised the dependence of these terms from t by a Receiver Operation Characteristic (ROC) curve using the R-Package *ROCR* (Sing et al., 2009).

3.2.5 Methods of the exposure analysis

The exposure analysis investigated the change in frequency of severe storm events. Gust speeds of 10 Bft (24.5 $m \; s^{-1}$) uproot trees and 11 Bft (28.5 $m \; s^{-1}$) cause widespread storm damage (WMO, 2009). Similar critical wind speeds were derived from mechanistic windthrow models (Ancelin et al., 2004; Zeng et al., 2010). As trees which are exposed to higher wind loadings over their lifetime could be more resistant (Ruel, 1995), high wind speeds are only a proxy for storm exposure.

We therefore used local percentile values of daily peak wind speed above which storm damages are expected as applied in other studies on wind damages (Klawa and Ulbrich, 2003; Pinto et al., 2010). Gusts of 30 $m \; s^{-1}$ to 40 $m \; s^{-1}$ occurring during the storm event Kyrill approximately correspond to the 99.95th percentile of peak wind speed in 1991-2009 (DWD, 2010) for four stations analysed (see Fig. 3.2). This threshold also encompasses velocities of other severe winter storms (Kunz et al., 2010). For both climate models, we therefore calculated the annual number of days with gusts exceeding the 99.95th percentile of the base line period (1971-2000, BASP) for the simulation period (2031-2060, SIMP) and BASP. We defined storm exposure as the difference between the number of these extreme storm days in the SIMP and the BASP.

Using the smooth operator of the program Climate Data Operators (CDO), we spatially averaged results of the climate models over nine neighbouring cells. We tested simulations for the BASP on plausibility using observed data of the four climate stations for the period 1991-2000 (DWD, 2010, Fig. 3.2). We viewed this to be sufficient, as CCLM and REMO wind speed outputs have already been extensively validated in former studies (Rockel and Woth, 2007; Kunz et al., 2010). Finally, we converted wind data to a 50 m grid in order to combine them with the sensitivity index.

3.2.6 Methods of the potential impact index

The sensitivity index p specifies the storm damage probability whose reciprocal is equal to the storm damage recurrence rate. For example, for p=0.1 storm damage occurs for every tenth storm of Kyrill-like strength. With regard to its peak wind speed of around the 99.95th percentile of 1991-2009, we assume Kyrill to be representative for future storms. Thus, combining p with the frequency of a 99.95th percentile storm results in an absolute damage recurrence measure of the potential impact I_τ of winter storms on forests under a changing climate:

$$I_\tau = \frac{1}{p_\tau \;\; [(1-\tau) \; 365 + \Delta C_\tau]} \tag{3.4}$$

where τ is a certain percentile for the daily gust speed, p is the storm damage probability depending on τ, $(1-\tau)$ 365 is the present annual number of days on which the daily maximum wind speed exceeds the τ-th percentile and ΔC_τ is the future change in this number. We applied formula (3.4) to each grid cell in NRW by setting τ=99.95% and assuming p_T to be constant during the evaluation period.

3.3 Results

3.3.1 Results of the sensitivity analysis

The logistic regression analysis to derive sensitivity of forest stands to windthrow based on biological, pedological and topographical parameters was carried out for two mutually exclusive datasets (samples S1 and S2). The regression models for both samples were nearly similar. However, S1 showed a higher model fit than S2 and is therefore discussed in more detail in the subsequent analysis (parameter estimates are presented in Table 3.2). For both samples, the backward selection procedure led to the exclusion of two variables: "deciduous forest" due to a moderate negative correlation with "coniferous forest" and "northern slope" due to a moderate negative correlation with the three other orientation variables.

According to the Wald statistics, the b_i of the remaining 19 variables were significant on a level <0.05, except for "natural forest reserve" and "depth to groundwater table". Standardised parameters b_i^* indicated a strong level of evidence for coniferous forests to be highly damage prone. Damage probability increased with soil erodibility, the existance of mixed forests, altitude, cation exchange capacity, curvature, infiltration capacity and distance to forest edge and decreased with soil quality, soil moisture level, slope and grain size. Storm damage probability was lower on eastern, southern and western than on northern slopes. Of negligible influence were air-filled porosity, hillshade, depth to groundwater table and the existance of natural forest reserves.

The concrete effect of each variable on the damage probability is represented by the odds ratio Ψ. In coniferous forests, the odds as the ratio of the probability of a cell to be *damaged* to *not* to be *damaged* were eight times this ratio for non-coniferous forests. The odds of southern exposed slopes were 62% of the odds for any other orientation. Odds decreased by 5% with a one-unit increase in soil quality and by 9% with a one-rank increase in soil moisture level.

We visualised the influence of the threshold on model success by an ROC curve (Fig. 3.3) plotting the true positive rate against the false positive rate (1-true negative rate). Defining a cut-off t, above which a cell is predicted to be *damaged*, allows us to convert the continuous probability outcome into a binary value (*damaged* vs. *undamaged*). The closer the ROC curve, which is based on such a converted model, approximates the left and top border of the ROC space, the higher is its ability to correctly predict the grid cells' outcome. This is quantified by the area under the curve (AUC=0.76). We empirically found correctly classified cells to be maximised for t=0.07. In this case, the overall model accuracy was 0.71 with a true positive rate of 0.76 and a true negative rate of 0.65, regardless of whether we applied the model to S1 or S2. Thus, *damaged* cells were better represented than *undamaged* cells.

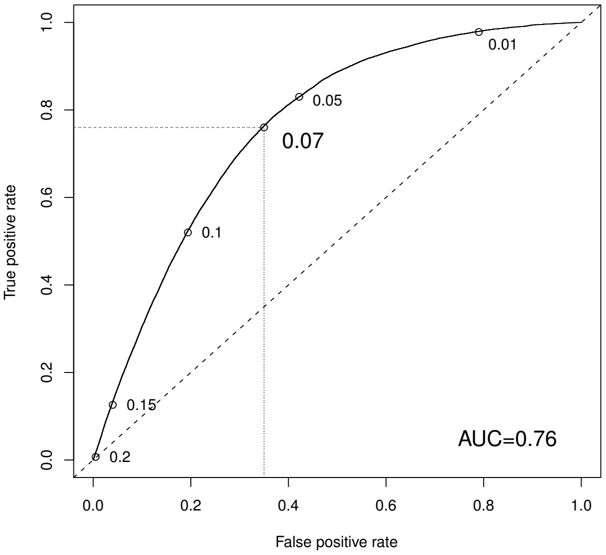

Figure 3.3: ROC curve of the applied logit model based on sample S1. Exemplary cut-off values t are marked, above which a cell is coded as damaged and otherwise as undamaged. The cut-off value t=0.07 resulting in the highest overall model accuracy is marked by vertical lines. The diagonal line (dotted) represents a random model.

The model parameters should be treated with caution as their underlying variables explained only D^2=11% of the variance of the outcome variable KYR (Table 2.2). Alternative goodness of fit measures indicated similar results. The third model fitted to the data of sample S3 explained a very low variance of D^2=2%. The D^2 was highest for the model based on the sample S1, which we

Table 3.2: Output of the logit model for the samples S1 and S2 sorted by b_i^*.

	Sample S1				**Sample S2**
Code	b_i	b_i^*	Ψ	**CI**(Ψ)	b_i
b_0	-3.82E+00***	-	2.19E-02	1.69E-01	-3.90e+00***
CON	2.08E+00***	4.56	7.99E+00	5.74E-02	2.08e+00***
ERO	2.49E-03***	0.99	1.00E+00	2.79E-04	2.42e-03***
MIS	5.62E-01***	0.98	1.75E+00	7.48E-02	6.02e-01***
ALT	1.26E-03***	0.90	1.00E+00	1.13E-04	1.10e-03***
CEC	1.82E-03***	0.55	1.00E+00	3.67E-04	1.61e-03***
CUR	3.24E-01***	0.50	1.38E+00	4.14E-02	3.50e-01***
ICA	1.38E-01***	0.38	1.15E+00	4.14E-02	1.55e-01***
DIS	2.31E-04***	0.18	1.00E+00	7.44E-05	2.73e-04***
DGT	4.74E-03	0.09	1.00E+00	6.18E-03	5.92e-03.
NFR	-6.02E-04.	-0.11	9.99E-01	6.65E-04	-9.22e-04*
HIL	-1.65E-03**	-0.16	9.98E-01	1.04E-03	-2.02e-03***
AFP	-1.88E-03**	-0.23	9.98E-01	1.31E-03	-2.06e-03**
GSZ	-4.69E-02***	-0.34	9.54E-01	2.06E-02	-3.60e-02***
SLO	-1.68E-02***	-0.48	9.83E-01	2.75E-03	-1.74e-02***
WSL	-2.65E-01***	-0.50	7.67E-01	4.68E-02	-2.14e-01***
ESL	-4.01E-01***	-0.73	6.70E-01	3.78E-02	-3.49e-01***
SSL	-4.73E-01***	-0.90	6.23E-01	3.62E-02	-4.83e-01***
SML	-8.96E-02***	-1.19	9.14E-01	7.99E-03	-8.99e-02***
SQT	-4.70E-02***	-1.83	9.54E-01	2.73E-03	-4.40e-02***

Significance codes: "***"=0.001, "**"=0.01, "*"=0.05, "."=0.1, " "=1. D^2=0.11 (0.11), McFadden's R^2=0.11 (0.11), Cox and Snell Index=0.05 (0.04), Nagelkerke Index=0.13 (0.13), Values are based on sample S1 (S2). Abbreviations: b_0=Intercept, b_i=Parameter estimate, b_i^*=Standardised parameter estimate, Ψ=Odds ratio, CI=95% confidence intervall.

therefore applied to all grid cells in NRW.

The resulting map showed predicted windthrow probabilities of 0-50% given a storm event of Kyrill-like strength (Fig. 3.4). Storm damages were highly probable in Sauerland and Eifel with values of ≥5%. Note the relatively high values in the western part and low values in the remaining part of the Westphalian Bight. According to the average over municipalities, the lowest mean sensitivity (p=0.3%) was found in Gladbeck in the Lower Rhine region with probabilities of not more than 1.7%. Most sensitive was Neuenrade in northwestern Sauerland (p=9.5%) where a large number of cells was predicted to have a storm damage probability of ≥10%. The highest standard deviation of all municipalities was found in Herscheid in western Sauerland with a value of 0.056 indicating high and low sensitive regions to be in close vicinity. Areas with a high storm damage probability (p ≥10%) corresponded well with observed storm damage occurrences.

3.3.2 Results of the exposure analysis

At first, we validated outputs of the used regional climate models against observed data for four climate stations (see Fig. 3.2) for the period 1991-2000, considering grid cells closest to the respective station. Generally, moderate extreme values were mostly higher (lower) for REMO (CCLM) compared to measured data, whereas extreme outliers were underestimated by both models. Observed values in Duesseldorf and on Kahler Asten were better represented by REMO, whereas CCLM was able to better capture the storm characteristic of Aachen and Muenster. With regard to the 99.95th percentile gust speed, REMO projected larger spatial differentiations, strongly controlled by the topography, compared to CCLM (not shown).

A more detailed comparison between both regional climate models is provided in Fig. 3.5, showing the distribution of wind speeds for the time periods BASP and SIMP. Curves for CCLM peaked at 8 $m\ s^{-1}$ and for REMO at 11 $m\ s^{-1}$ whereby the latter projected more extreme values. Whereas CCLM simulated 99.95th percentiles for the BASP of 24 $m\ s^{-1}$, REMO projected values of 28 $m\ s^{-1}$ with increases in the SIMP by 3% (REMO) and 1-5% (CCLM). This is remarkable, since model differences were distinctly greater than climate change signals.

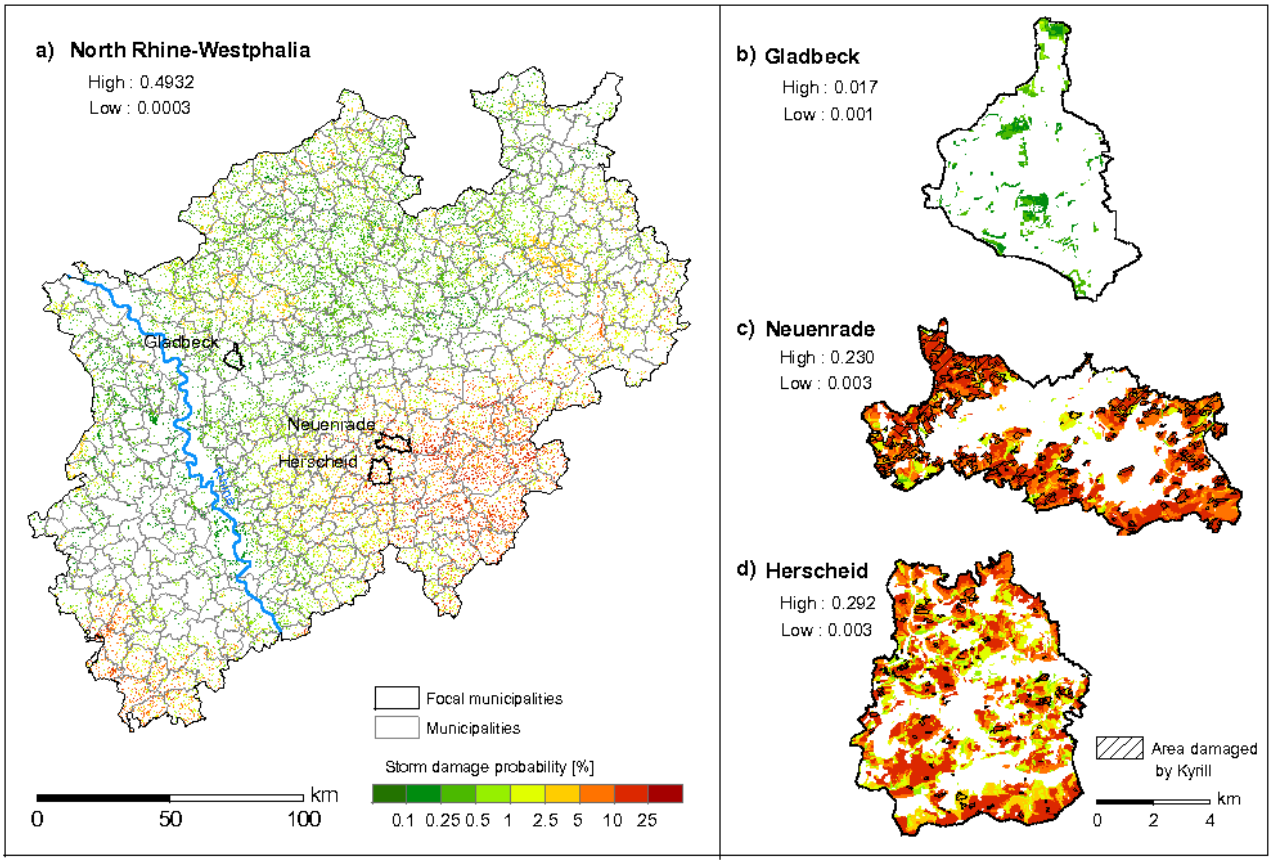

Figure 3.4: Sensitivity of forests to storm damage expressed by storm damage probability in (a) NRW, (b) Gladbeck, (c) Neuenrade and (d) Herscheid.

The annual number of days with gusts exceeding the 99.95th percentile of the BASP was simulated to increase by 0.6 days in the SIMP in the Eifel and Sauerland region for both models (Fig. 3.6). Hence, the return period of such an event decreased from five years to one year. For the lowlands, CCLM projected them to double in frequency, while the trends simulated by REMO were generally lower and differed more between low-lying areas. Regions where both models projected a similar change are marked in Fig. 3.6. The agreement was found to be high in the Westphalian Bight, Eifel, eastern Sauerland and along the Rhine. Low agreements occurred in the western Sauerland, Lower Rhine Embayment and the northwestern part of NRW.

3.3.3 Results of the potential impact analysis

The combined effect of sensitivity and exposure, which represents the potential impact of storms of Kyrill-like strength, is shown in Fig. 3.7 for each municipality. Impacts are shown for a steady state scenario ($\Delta C_{99.95\%}=0$) and future climate change signals for 99.95th percentile events simulated by CCLM and REMO.

For the steady-state scenario, storm damage recurrence intervals of 100-250 years in Sauerland and thousands of years in the Lower Rhine Embayment can be seen. Over all time periods, mountainous areas exhibited the highest impact. For the future, a strong rise in storm damage probability was projected, with recurrence intervals decreasing to 50-100 years until 2060 for the majority of the mountain ranges. Besides this, the present medium potential impact level in these regions was simulated as affecting the mountain foothills in the future. Especially in the hills in the eastern and northwestern part of NRW a strong rise in storm damage frequency from 500-1000 years to 100-250 years is apparent until 2060. These tendencies are true for both models. However, CCLM simulated generally higher increases in potential impacts compared

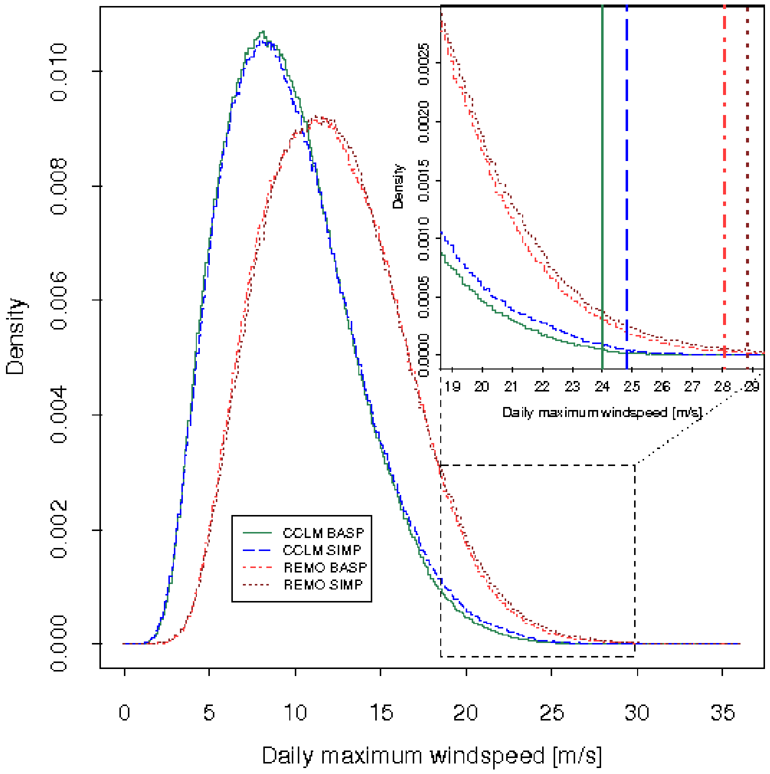

Figure 3.5: Histogram of the daily maximum wind speed simulated by REMO and CCLM (mean over all model runs) for the periods BASP and SIMP averaged over NRW (class width = 0.1 m s^{-1}*). The upper tail of the distribution is depicted in more detail by the inset. The vertical lines highlight the 99.95th percentile values for each curve.*

to REMO so that more municipalities reached the highest impact level with storm damage recurrence intervals of less than 50 years. REMO projected higher potential impacts for the northwestern part of NRW, whereas CCLM simulated higher ones for the southern Westphalian Bight, Bergisches Land and western Sauerland. The Lower Rhine Embayment is the only region in NRW for which REMO simulated potential impacts to slightly decrease, whereas CCLM simulated them to increase.

3.4 Discussion

We investigated potential impacts of winter storms on forests in NRW under changing climate conditions by performing a sensitivity analysis based on logistic regression and an exposure analysis based on a statistical evaluation of simulated wind climate data.

The goodness of fit of the logit model proved to be poor, which could be due to the low proportion of *damaged* cells, contributing to low damage probabilities and thus large residuals. The overall model accuracy of 0.71 for t=0.07 was satisfactory, however it is known to be usually higher for models based on data with a highly unbalanced proportion of *damaged* and *undamaged* cells (Dobbertin, 2002). In this case, neural network approaches may provide better fits than logit models (Hanewinkel et al., 2004). An explained variance of 11% found for the 'best' model is not uncommon in windthrow modelling using logistic regression. Similar results were found by Schütz et al. (2006) for the prediction of storm damages in Switzerland and by Jalkanen and Mattila (2000) in northern Finland. Mayer et al. (2005) obtained an R^2 of 21% for their model applied to forests in France, Southern Germany and Switzerland. Furthermore, other studies applying various statistical or mechanistic methods reported prediction accuracies similar to the ones reported here (Scott and Mitchell, 2005; Dobbertin, 2002; Gardiner et al., 2008). We may have reached a higher model accuracy

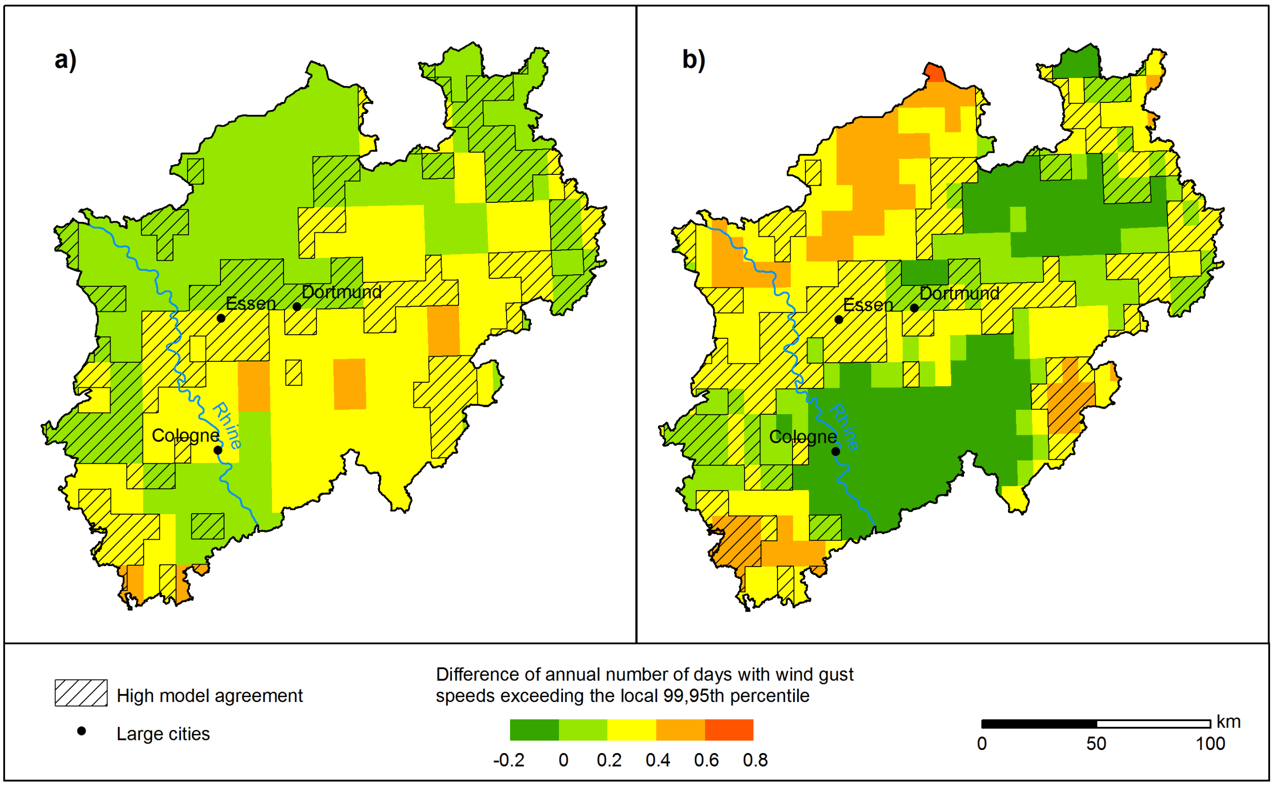

Figure 3.6: Difference of annual number of days with wind gust speeds exceeding the local 99.95th percentile of the BASP between both time slices simulated by (a) CCLM (mean over all model runs) and (b) REMO. Cells for which both models differ ≤0.1 days are marked with diagonal stripes.

by including data on stand characteristics (stand age, vertical structure, canopy and root conditions) and logging history as key influencing factors for windthrow (Aldinger et al., 1996; Jalkanen and Mattila, 2000; Dobbertin, 2002; Hanewinkel et al., 2004; Scott and Mitchell, 2005; Zeng et al., 2010). For example, stand age was of importance for forests in Sauerland damaged by Kyrill (Spelsberg, 2008). As the D^2 of 2% of the sample S3 indicates that included parameters hardly differed between damaged areas and their undamaged immediate surroundings, the remaining explanatory variable could be the wind speed. During the passage of Kyrill, the wind field was highly variable and more connected to convective events than to the local topography (Fink et al., 2009). This is especially relevant considering that in other contexts extreme wind gusts have been recorded to reach a value where local characteristics became irrelevant for storm damage (Schmidtke and Scherrer, 1997; Ancelin et al., 2004).

This raises the question of whether Kyrill is representative of winter storms in NRW. Although gale-force winds covered an unusually large area (Fink et al., 2009) the wind field of Kyrill is comparable to other past winter storms (MunichRe, 2007). In addition, factors that have contributed to the genesis of Kyrill are expected to occur more often under global warming so that Kyrill can be regarded as representative of severe present and future winter storms (Fink et al., 2009). However, Dobbertin (2002) showed by comparing two storm events in Switzerland that damage patterns of storms could differ markedly from each other.

We have shown that coniferous forest is more sensitive to storm damage than deciduous or mixed forest, which is generally accepted in the literature (Ruel, 1995; Aldinger et al., 1996; Polomski and Kuhn, 2001). Reasons include the higher wind load, superficial rooting, higher stocking, lower diameter at breast height and higher height to diameter ratio of coniferous trees as compared to deciduous trees. Also, spruce and pine roots are known to be more

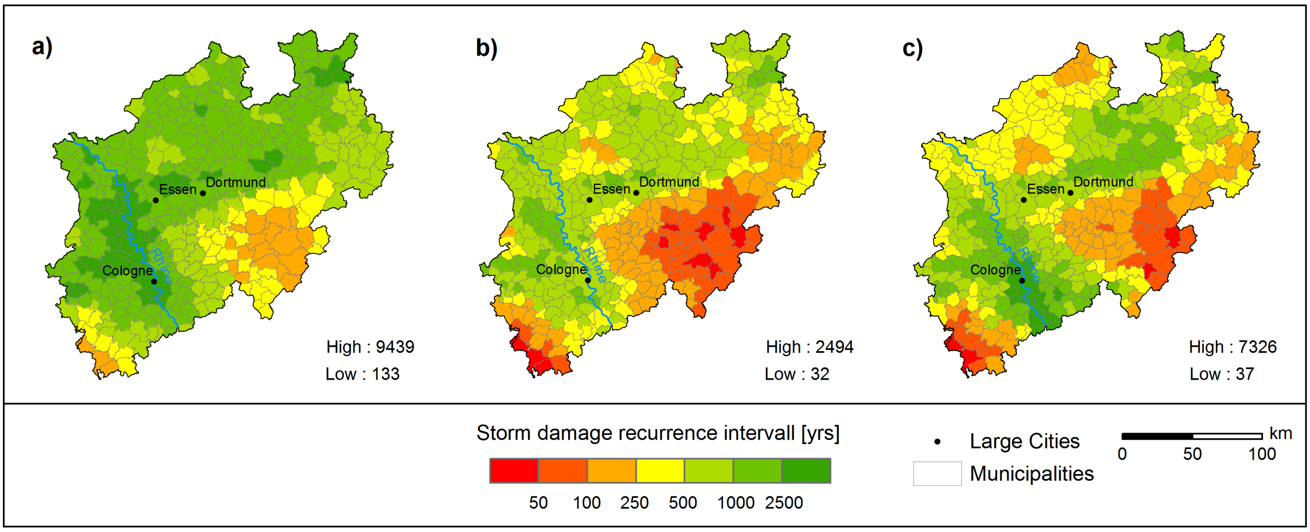

Figure 3.7: Potential impact of winter storms on forests operationalised as the storm damage recurrence interval according to (a) a steady state scenario ($\Delta C_{99.95\%}=0$), (b) CCLM simulations (mean over model runs) for the SIMP and (c) REMO simulations for the SIMP.

prone to diseases and root rot than beech or oak roots (Aldinger et al., 1996). Note that deciduous trees can also be sensitive when they are in leaf (Peltola et al., 2010); an early autumn storm could cause severe damage in deciduous stands (Nilsson et al., 2004). However, the number of storms in Europe is much lower in summer (MunichRe, 2007) and we did not find notable increases in the 99.95th percentile of daily maximum wind speed for NRW in summer until 2100 according to CCLM and REMO (not shown).

Distance to forest edge was shown to have no significant impact on storm damage probability, which is confirmed by Schindler et al. (2009). However, we did not differentiate between forest edges that have existed for a long time and newly created edges. The latter are regarded to be high risk areas for windthrow, especially in stands dominated by Norway spruce (Zeng et al., 2010). Natural forest reserves were less damage-prone than other forests in this study. This was also found by Schulte and Richter (2007) and can be explained by their high biodiversity and complex stand structure.

Storm damage probability increased with infiltration capacity and decreased with grain size. This is controversially discussed in the literature (Mayer et al., 2005; Dobbertin, 2002; Scott and Mitchell, 2005). Heavy precipitation occurring during the passage of Kyrill (Fink et al., 2009) might have contributed to a reduced shear strength of fine-grained soil and a loss of root anchorage (Panferov et al., 2009). Also, fine-grained soils limit root growth and have a higher tendency to root rot compared to coarse-grained soils (Aldinger et al., 1996; Polomski and Kuhn, 2001).

A low water table and soil moisture enhanced the storm damage probability. These two parameters showed a weak negative correlation with altitude. Thus, the mentioned levels occurred more often on sites with pontentially stronger winds. Our results contrast with studies finding moist and waterlogged soils with a near-surface water table to be the most sensitive, since they only allow shallow rooting (Polomski and Kuhn, 2001; Dobbertin, 2002; Schindler et al., 2009). This was especially relevant in the Sauerland with respect to damages caused by Kyrill (Asche, 2008). We also showed that damage probability increased with cation exchange capacity. Assuming that this parameter would increase with the pH-value, our findings contrast with results from Mayer et al. (2005) suggesting acidic soils to be associated with a stunted growth of fine roots contributing to a reduction in tree stability. However, the influence of cation exchange capacity on acidity (Ross et al., 2008) and root anchorage (Polomski and Kuhn, 2001) is controversial. Furthermore, cation exchange capacity showed a moderate negative correlation with grain size, which could explain the found relationship. Soil quality and storm damage probability proved to be antagonistic in the present study. Trees on nutrient-rich soils may be more vital and stable. A low soil quality, however, could force trees to develop a more branched rooting at the expense of stem and canopy growth (Heinrich, 1991).

Our findings suggested storm damage probability increases with altitude, whereas studies on other storm events and regions showed no clear relation (Dobbertin, 2002; Mayer et al., 2005; Schmoeckel and Kottmeier, 2008). We also showed storm damage to rise with decreasing slope, which is in line with Hanewinkel et al. (2004). Nevertheless, there is evidence that trees on medium slopes, where root anchorage tends to be limited under wet conditions, are most sensitive (Dobbertin, 2002; Schmoeckel and Kottmeier, 2008; Schmidtke and Scherrer, 1997; Mayer et al., 2005). This could not be represented by our logit model. We found that damage probability increased with curvature and decreased with hillshade. The first result is supported by findings from Ruel (1995) and Schmidtke and Scherrer (1997). The second result is in line with Asche (2008) who explained severe storm damage on sheltered sites in valleys in Sauerland by pipe effects. We further provided indications that trees on east, south and west facing slopes are less sensitive than on northern slopes. A large disagreement exists in the literature on whether slopes parallel (Schmoeckel and Kottmeier, 2008) or perpendicular (Mayer et al., 2005; Scott and Mitchell, 2005) to the prevalent wind direction are most sensitive or whether sensitivity is independent of orientation (Hanewinkel et al., 2004).

We found a highly spatially heterogeneous pattern of sensitivity for the municipalities in NRW. The exceptionally low sensitivity of Gladbeck can be attributed to a large share of deciduous forests, a less complex terrain and low altitudes. These factors are more important than the relatively sensitive stagnosols and gleysols with loamy clay, different moisture levels and a low to medium soil quality and erodibility. Parameters contributing to the high sensitivity of Neuenrade included a large share of coniferous forest, a complex terrain with altitudes of 300-500 m and gentle to steep slopes. Soils are characterised by cambisols with highly sensitive clayey silt and alternating or dry soils with a medium soil quality and erodibility. Similar soil characteristics can be found in the municipality Herscheid. However, their greater spatial differentiation is reflected by a highly complex terrain with moist soils in deep valleys and dry soils on hilltops. These structures are mirrored by a differentiated forest structure, whereby coniferous forest dominates over deciduous and mixed forests.

When interpreting the parameters it has to be mentioned that the logit model may simplify complex relationships between storm damage probability and parameters. Their interpretation is further complicated by the possible multicollinearity of input data. For the calculation of sensitivity, however, priority is given to maximising the model accuracy rather than revealing causal structures.

The exposure analysis has shown that both climate models, REMO and CCLM, underestimated the magnitude of severe gusts. Kunz et al. (2010) and Rockel and Woth (2007) found this systematic underestimation to be 10% for REMO and 25% for CCLM with the highest values in complex terrain. This can be due to the low resolution of regional climate models. On Kahler Asten, wind speed is measured at an altitude of 839 m.a.s.l., but simulated for an altitude averaged over eight neighbouring cells of 559 m.a.s.l. (REMO) and 452 m.a.s.l. (CCLM). Besides, regional climate models fail to capture local surface-induced gusts and convective mesoscale storm features that were particularly connected with extreme gusts of cyclone Kyrill (Fink et al., 2009).

Fortunately, systematic model errors are mitigated when calculating the difference in the annual number of days with 99.95th percentile storms. We showed that their simulated increase is higher for CCLM than for REMO, ranging from a slight decrease to a rise of up to 200%. Others projected the annual number of days with gusts ≥ 8 Bft to increase by 10-20% (CCLM) and 5-15% (REMO) until 2100 in Western

Germany (Rockel and Woth, 2007; Fink et al., 2009). According to a mesoscale model, the number of weather patterns in NRW typically associated with winter storms is expected to increase, especially in northern and northeastern NRW, under the scenario A1B (Pinto et al., 2010). In contrast, we found the increase in storm frequency to be largest in southern and southeastern parts of NRW. Although CCLM and REMO do not agree in general in terms of spatial characteristics, they mostly point in the same direction which is supported by results from an ensemble of regional climate models for Central Europe (Rockel and Woth, 2007).

Spatial patterns of the exposure index (Fig. 3.6), especially the differences between the two included regional climate models, were to some extent reflected by the potential impact measure (Fig. 3.7). Furthermore, our potential impact index showed spatial patterns similar to the relative measure by Kropp et al. (2009). However, our index is more meaningful in absolute terms, since it includes the storm damage recurrence time ranging from a few to thousands of years in NRW. Schütz et al. (2006) found storm damage recurrence intervals of around 90-410 years for the Swiss Midlands. Similar to our results, increasing storm damage probabilities under changing climate conditions until 2100 were simulated for two Swedish forests, explained by an increasing tree productivity, more frequent thinnings and an increasing storm frequency (Blennow et al., 2010), and for a forest in Weserbergland, Germany, due to increasing maximum wind speeds and precipitation and thus soil water contents (Panferov et al., 2009).

Our potential impact index is mainly limited by the calibration by means of a singular storm event. Therefore, it is essential to include high resolution storm damage data from several events into future studies. In spite of the application of regional climate models to project storm conditions, spatial resolution is still rather low compared to the pedologic, forest and topographic data included in the analysis. Further regional differentiation of climate models could thus improve our results. Moreover, we assume that soil and tree characteristics will remain constant until 2060. In fact, soil parameters may change within decades (Mayer et al., 2005). Furthermore, climate change could induce altering growth conditions with increasing temperature, which leads to a changing tree species composition (Peltola et al., 2010) and forest productivity (Blennow et al., 2010) associated with increasing sensitivity under the current management regime. Besides, increased storm damage in Switzerland in the 20th century were associated with increasing temperature and precipitation (Usbeck et al., 2010). Similar trends in these climate parameters were also simulated for NRW especially for the winter time (Kropp et al., 2009). Storm damage sensitivity can also be modified by changing management regimes and thinning schedules (Schelhaas et al., 2003; Nilsson et al., 2004) determining the creation of new highly vulnerable edges (Zeng et al., 2010). For these reasons, our potential impact index represents a hypothetical storm damage recurrence time regardless of former logging and storm activities or future changes in the forest structure due to adaptation or silvicultural operations.

3.5 Conclusions

We developed an innovative approach to assess future potential impacts of winter storms on forests in NRW by combining their sensitivity and exposure to a single metric. Sensitivity is defined here as the storm damage probability and was calculated by applying a logistic regression model explaining damage patterns of a past event. Exposure was operationalised as the change in the frequency of devastating storms and derived from two regional climate models.

Our impact analysis provides a measure of the recurrence time of future storm damages occurring above specific local percentiles of wind speed. The methodological approach is well transferable to forests with similar structure where wind damage results from large-scale extratropical cyclones. However, the threshold values for maximum wind speed need to be adjusted to severe storm events for other regions. In principle, our sensitivity model is also applicable to similar regions, but should be locally validated.

A major benefit is the provision of a basis for the implementation of adaptation measures. Our impact maps can be used by decision makers to identify regions particularly vulnerable to storm damage. Sensitivity maps in combination with more detailed field studies would help foresters in implementing silvicultural operations. In particular, the high positive contribution of coniferous forest to storm damage probability suggests to convert coniferous forests to mixed or deciduous forests. Our results on soil parameters highlight the importance of implementing amelioration measures improving stand vitality and soil moisture regime. Forest protection measures should also include a reevaluation of silvicultural practices. However, the acceptance and implementation of forest protection measures could be complicated by the ownership structure, since two-thirds of the forest area in NRW is privately owned but showed 80% of timber damaged by Kyrill (MUNLV, 2010).

To provide a broader picture of possible outcomes, subsequent studies should include scenarios of different forest management strategies, further climate models and scenarios with a higher spatial resolution and additional climate variables such as temperature and precipitation. Also, stand and treatment characteristics and their dynamics under climate change using forest growth models could improve the sensitivity model. The inclusion of storm damage data from several events would enhance the representativity of our index. In this context, it would be highly desirable to apply our methodology to another storm event for the same region.

Kyrill can be regarded as a reminder of the urgency to rethink existing silvicultural paradigms. Impact assessments constitute the first step towards vulnerability measures and have to be complemented by the identification and quantification of adaptive capacity in order to provide guidelines for foresters and decision makers.

4

Evaluation of the Performance of Meteorological Forest Fire Indices for German Federal States*

Abstract

Meteorological forest fire risk indices have been developed to forecast the risk of fire occurrence and aid forest managers to take suitable preventive measures. We evaluate five meteorological fire risk indices and relevant meteorological variables for their predictive capacity against monthly fire statistics for 13 German states between 1993 and 2010. Mean relative humidity stands out as the best overall predictor (for 9 out of 13 states) for the recorded number of fires with a median correlation coefficient for Germany of -0.7. The indices with best explanatory power were, in increasing order, the German modified M-68, the Canadian Fire Weather Index and Angström. The correlations of fire data with relative humidity and fire indices were higher for states particularly prone to fire occurrence. At the monthly scale, correlations of relative humidity and fire indices with area burnt are in average lower than with the number of fires. For the same time period, we investigated the performance on a daily scale for the state of Brandenburg. In this case, the performance of fire indices and relative humidity were more similar than at the monthly level. In addition, the number of fires could be explained equally well as the area burnt. Climate projections under different temperature and moisture conditions consistently indicate a monthly decrease in relative humidity until 2060, particularly in the summer months. Future monthly values of M-68 also denote a considerable increase of fire risk in summer. The increase in fire risk at the beginning and end of the fire season points to a possible extension of the current fire season. Our results reveal that mean relative humidity is sufficient to describe observed fire occurrences in Germany at both monthly and daily scales. Correlation coefficients were robust in state, country, monthly and daily analysis. Due to its predictive power and simplicity of calculation, relative humidity is a valid or better alternative in Germany as a proxy for monthly forest fire risk.

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4.1 Introduction

Forest fires are considered a major disturbance in forest ecosystems. Their occurrence can lead to considerable ecological and economic losses as well as global CO_2 emissions comparable to those from fossil fuel combustion (Bowman et al., 2009). Because of their ability in providing quantitative estimates on the chance of forest fires' occurrence, fire risk indices based on weather data have become important tools in evaluating regional fire risk potential over time. Although the existence of strong correlations between fire occurrence and weather conditions (Viegas et al., 1999; Carvalho et al., 2008; Flannigan et al., 1998) supports the rationale behind using weather-based indices for fire risk forecasting, their ability in describing observed fire patterns has been reported to vary within the respective season. For example, after testing several fire risk indices in the Mediterranean region, Viegas et al. (1999) concluded on the existence of seasonal variability regarding the predictive quality of fire indices; namely between summer-autumn and winter-spring fires. In addition, the explanatory power of fire indices varied considerably at spatial scales below national (Padilla and Vega-García, 2011). The use of fire indices for preventive planning requires therefore a thorough evaluation of their spatial and temporal applicability.

In Germany, two meteorological fire indices have been developed to evaluate fire risk on a daily basis - the M-68 and the Baumgartner Index. The latter was used in former West Germany, while the M-68 was originally developed and applied in former East Germany (Käse, 1969; Flemming, 1994). The M-68 – in a modified form – is currently the standard index used by the German Weather Service (DWD) to provide forest fire risk on a daily basis. Both indices have been subject to evaluations of performance on annual (Badeck et al., 2004) and daily levels (Wittich, 1998). However, their comparison was temporally restricted to yearly numbers of forest fires or to a time frame of one year, respectively, and geographically limited to one federal state in both studies. It remains an open question to what extent commonly used fire risk indices like the Canadian Fire Weather Index (FWI), a sub system of the Canadian Forest Fire Danger Rating System (CFFDRS), the Angström index or the Nesterov Index provide an alternative, or a complement, to the M-68. With a comprehensive analysis on fire indices' performance at German state level still missing, there is also a lack of information on how much the fire indices better aid predictability compared to using raw weather variables. This is a relevant point to consider since it is known that fire indices are particularly sensitive to input variables such as rainfall, temperature and wind conditions (Dowdy et al., 2010). Finally, while the increase in fire risk at large spatial scales due to climate change has been established (Marlon et al., 2009; Lindner et al., 2010), researchers have been making use of fire risk indices to assess climate change implications in fire regimes at national levels (Carvalho et al., 2011; Giannakopoulos et al., 2009).

In this paper we aim at filling in the existing knowledge gaps on the relations between fire occurrences and climate conditions in Germany by providing a comprehensive comparison of the monthly performance of multiple forest fire indices for 13 states as well as their performance on a daily level for one state. In addition, we test the explanatory power of fire indices against their raw input variables and evaluate if the modified M-68 - commonly applied in Germany - shows the overall best performance. We then analyze the potential future monthly fire regime in Germany under climate change based on the best performing approach identified.

4.2 Study area description

In general, Germany is characterized by a temperate climate with maritime components near the North and Baltic Sea and continental influences increasing in south-east direction. Maximum daily temperature ranges between 12.9 °C and 14.1 °C among the states, annual precipitation between 620–1000 mm averaged over Germany during 1993–2010. With an annual sum of about 600 mm during this time period, BB is the driest state, while Baden-Württemberg (BW) Bavaria (BY) and North Rhine-Westphalia

(NW) are among the wettest with over 1000 mm. Around 31 % of Germany is covered by forests (BMELV, 2005), dominated by Norway spruce, Scots pine, European beech and oak. Historically, the drier and pine-dominated region of the north-eastern German lowlands has been the most fire prone area. Exceptional conditions of high temperatures and low values of precipitation and relative humidity were recorded in the year 2003, together with comparatively high fire activity. Germany comprises 16 Federal states, three of which are city states which account for less than 0.2% of total forest area (Fig. 4.1). An overview over the characteristics of the considered states regarding climate, forest cover and forest fires is provided in Table 4.1.

4.3 Data

We obtained data on the monthly numbers of forest fires and area burnt from annual reports of the German Federal Agency for Agriculture and Food (BLE) for each Federal State. We restricted our analysis to the years 1993-2010, where monthly fire statistics for both public and private owned forests are available. Further, we obtained daily forest fire data for the state of BB from the Federal Forestry Office Brandenburg for the same time period. Climate data from the German Weather Service (DWD) for 1218 operating measurement stations (Fig. 4.1) was used for the calculation of fire risk indices. This dataset comprises daily values of maximum, mean and minimum temperature, total precipitation, and means of relative humidity, air pressure, water vapor pressure, sunshine hours, cloudiness, radiation and wind velocity. Additionally, noon relative humidity was calculated based the long-term climate data of the Potsdam weather station, BB, between 1893–2010.

For future projections of fire risk, we use the climate data from the STAtistical Resampling Scheme (STARS, version II) (Werner and Gerstengarbe, 1997; Orlowsky et al., 2008), with a simulation period from 2007 to 2060. For this simulation, observed climate data is resampled using a cluster analysis, whereby different temperature trends from 0 to 3.0 K increasing in steps of 0.5 K are imposed (Werner, 2011). We evaluate future fire risk for a 1 K, 2 K and 3 K temperature rise under medium humidity conditions. Complementarily, for the 2 K rise scenario, we analyze future fire risk under relatively dry and wet conditions. All the temperature scenarios are in principle equally probable as they depend on future global demographic trends and greenhouse gas emission rates that cannot be exactly anticipated. The different humidity conditions are generated from different runs of this stochastic model. Model data before 2007 represents the observed climate data from DWD for a larger set of climate stations (2337), as more stations were in operation until then (see Fig. 4.1). Missing climate data was spatially and temporally interpolated by the Inverse-Distance Method (taking a maximum of 5 surrounding stations into account) and for temperature and air pressure, a correction based on elevation was applied. This is due to the larger spatial coverage of precipitation measurements than e.g. temperature measurements. This interpolation was applied to the dataset of observed climate, on which the simulation of climate for the projection period is then based. To compare past and future climate and fire regime conditions, we use data of the STARS model for the time frames 1961-1990 and 2031-2060.

Finally, we weighted the fire risk indices for each station by the proportional area of the surrounding forest cover to reduce the bias from inhomogeneous distribution of forests. Forest cover for Germany was obtained from the CORINE Land Cover vector data (CLC2006) (EEA, 2006) by aggregating the broad-leaved (class 311), needle-leaved (class 312) and mixed (class 313) forest classes.

4.4 Methods

We calculate five meteorological fire risk indices and test their ability to reproduce the monthly pattern of forest fire statistics in German federal states. Station based daily fire indices were calculated and spatially and temporally aggregated for analysis with the monthly fire statistics. A summary of the investigated risk indices, the required and applied input variables and meteorological variables used is provided in Tab. 4.2.

Two of these approaches were developed specifically for Germany—the Baumgartner In-

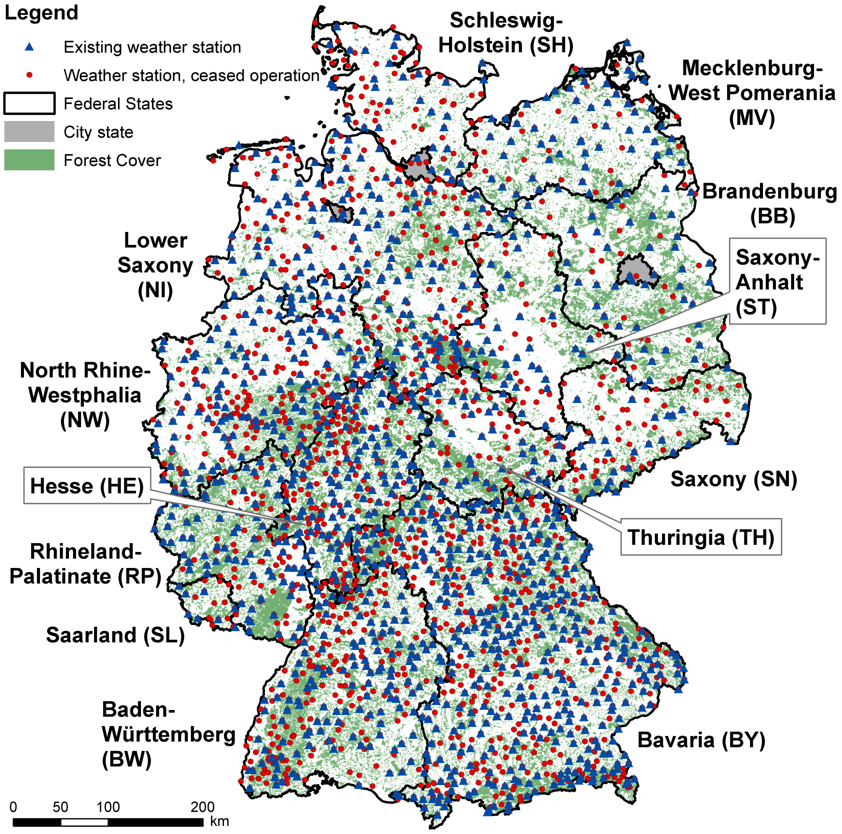

Figure 4.1: Location of weather stations and forested area within the German federal states. Only non-city states were analysed. Note that abbreviations referring to the federal states are introduced.

dex and the M-68. The former was developed for the state of BY and is based on precipitation and potential evapotranspiration of the previous five days (Baumgartner et al., 1967). Due to a lack of data, we calculated evapotranspiration with temperature, radiation and relative humidity according to the Turc/Ivanov method (Turc, 1961; Wendling and Schellin, 1986) (see also equation in the supplementary material). The M-68 is based on a formerly used index for East Germany (Käse, 1969; Flemming, 1994). Since the German unification the M-68 has been modified and is currently used as the standard index to provide forest fire risk on a daily basis by the German Weather Service (Friesland and Löpmeier, 2007). Additionally to weather data, the modified M-68 also requires phenological data, namely, the onset day of the bud burst of birch (*Betula pendula*) and robinia (*Robinia pseudoacacia*). Burst dates were calculated employing temperature sum models for birch (Schaber, 2002, p. 145) and robinia (Chmielewski et al., 2004, p. 75). Due to a lack of data, we substituted days with snow cover by snow days, defined as days with minimum temperature below 0 °C and precipitation above 0 mm. Thereby we underestimate the fire risk, however, this is expected to be a minor influence during the fire season. Based on applications of this index by Suckow et al. (2005); Badeck et al. (2004), we calculate the required saturated vapor pressure by using the daily maximum temperature according to Bolton (1980). As modifications of the index consider the fire proneness of the region (Landesforst Mecklenburg-Vorpommern, 1999), we classified BB as the highest fire prone state, Saxony (SN), Mecklenburg-West Pomerania (MV), Saxony-Anhalt (ST) and Lower Saxony (NI) as medium and the rest of the states with the lowest value, based on Wittich (2011). The Canadian FWI is currently used to forecast fire risk for whole of Europe by the European Forest Fire Information System (EFFIS) and its application to the global scale is also planned (Dimitrakopoulos et al., 2010). This complex index comprises six components providing probabilities of fire

Table 4.1: Overview of the states: Number of climate stations used for indices evaluation, mean annual temperature, annual sum precipitation sum (1993-2010), forest cover in ha (based on the applied database of forest fires), share of forest area compared to the state's area, Total number of fires and area burnt [ha] from 1993-2010. For abbreviations of the states, see Figure 4.1.

State	# Stations	Tmean [°C]	Prec. [mm]	Forest area [ha]	Forest area [%]	# fires	Area burnt [ha]
BW	130	9.3	986.8	1281409	35.8	479	164.6
BY	384	8.4	988.5	2386027	33.8	1318	1497.5
BB	43	9.4	584	973017	33	7261	4526.8
HE	109	9.4	775	813092	38.5	1074	255.9
MV	54	9.1	633.7	492673	21.2	1232	638.5
NI	141	9.6	817.8	1081248	22.7	1791	710.3
NW	121	9.8	949.7	835763	24.5	858	395.2
RP	75	9.6	774.1	794432	40	980	318.4
SL	8	10	892	92131	35.9	115	82.1
SN	31	8.3	838	471290	25.6	1564	913.6
ST	37	9.2	674.9	454640	22.2	2055	1157.6
SH	31	9.2	811.2	154602	9.8	172	58.3
TH	46	8.5	740.7	490276	30.3	493	138.9

ignition and fire behavior, and takes into account the effect of fuel moisture. The Angström index is based on atmospheric dryness of the same day Ångström (1942) and has been tested for other regions in Europe with satisfactory results (Skvarenina et al., 2004; Ganatsas et al., 2011; Reineking et al., 2010). Finally, the Nesterov Index was developed for use in Russia (Nesterov, 1949; Groisman et al., 2007). It has been used as a basis for the development of the German M-68 Index. The required dew point temperature was estimated via the relation between temperature, relative humidity and air pressure based on Martinez (1994). Except Angström, all indices are cumulative indices, in that fire risk of a particular day is also dependent on the weather conditions of the previous days. The M68, FWI and the Angström require noon relative humidity as an input. However, only data on mean daily relative humidity was consistently available for all climate stations. Where noon relative humidity was required, we adjusted the mean values of relative humidity according to the monthly differences observed between mean and minimum relative humidity for the long-term station of Potsdam. The differences ranged between 12 and 16 % between March and October of 1893–2010.

Absolute values of fire risk indices are often grouped into fire danger classes that provide a qualitative description of the risk for ease of applicability. We adopt the common terms danger classes, ranging from 5 (high) to 1 (low) and convert daily index values at state level into danger class according to the description of the respective indices. We apply the classification of the FWI as currently adopted to European conditions (Camia and Amatulli, 2010). The Angström index is classified according to Skvarenina et al. (2004). Note that the Baumgartner Index considers a classification dependent on the respective month (Baumgartner et al., 1967) and the danger classes of the modified M68 are dependent on the state and wind velocity (Landesforst Mecklenburg-Vorpommern, 1999).

Although fire index values could be calculated on a daily basis, fire statistics were only available at monthly level for each state. In order to compare index values from climate stations with monthly fire statistics of German states, we therefore aggregate fire index values spatially (state level) and temporally (monthly level). Because the reported number refers to fires that occur in forested areas, index values from stations with small forest area in their vicinity should in principle have a lower weight on the final fire index value when compared to those close to large forests. We therefore weighted the classified index value of each station by the share of forest within its surroundings (delineated by Thiessen polygons) before spatially averaging fire index values of stations over the respective state. Thus, each

Table 4.2: Overview of the considered forest fire indices and their input meteorological variables on a daily basis (Tmean=mean temperature, Tmax=maximum temperature, RH=relative humidity, RHnoon=noon relative humidity, RHadj= RH adjusted to represent noon relative humidity, P=precipitation, W=wind velocity, EP=potential evapotranspiration, R=radiation, SD=saturation deficit, DPT=dew point temperature, AP=air pressure)

Index	**Source**	**Original input**	**Applied input**
Baumgartner (Ba.)	Baumgartner et al. (1967)	P, EP	P, Tmean, R and RH
Modified M-68 (M-68)	Käse (1969); Flemming (1994), modified to account for wind and fire prone regions (Landesforst Mecklenburg-Vorpommern, 1999)	P, Tmax, W, SD, phenology (bud burst dates of black locust and birch)	P, Tmax, W, RHadj, Tmean
Canadian Fire Weather Index (FWI)	Van Wagner and Pickett (1985); Van Wagner (1987), classification after (Camia and Amatulli, 2010)	P, W, RHnoon	P, W, RHadj
Angström (Ang.)	Ångström (1942), applied in Skvarenina et al. (2004)	Tmax and RHnoon	Tmax, RHadj
Nesterov (Ne.)	Nesterov (1949), applied in Skvarenina et al. (2004)	Tmax, P, DPT	Tmax, Tmean, RH and AP

stations daily index value (from 1 to 5) is averaged over all the stations within a state to generate a single daily value for the whole state (classes as decimal number). The analysis has been carried out based on the index classes since the classification is inheritably included in the methods of some indices, e.g. the Baumgartner index applies month-specific classifications and the modified M-68 depends on wind velocity and geographic region for the classification. Further, the indices involve unequally spaced classes, according to their developed algorithms. To be able to compare the performance of all selected indices, we therefore focus their classified values. However, in order to test for possible losses of explanatory power due to the classification of index values into fire danger classes, we also correlated unclassified maximum and mean values of the Angström, FWI and Nesterov index with fire statistics. In these indices danger class classification is not an integral part of their calculation.

Regarding the temporal aggregation to the respective months, we calculated the monthly mean fire danger class as the monthly average of the above described classified index values for the specific state. Additionally we counted the number of days falling into different class combinations (i.e. days with danger class 5, days with danger classes 4 to 5, days with danger classes 3 to 5 and days with danger classes 2 to 5). We then correlated the index values (classified monthly mean and counts of danger classes) with observed monthly number of fires and area burnt for every state investigated.

In order to check the performance of raw weather variables, mean values of daily maximum and mean temperature, relative humidity and daily sum of precipitation were also considered in the correlations. These variables are the key inputs in most of the indices applied (Tab. 4.2) and are also considered in similar studies which analyze weather conditions during high fire seasons (Carvalho et al., 2010; Ganatsas et al., 2011; Skvarenina et al., 2004). They were weighted by the surrounding forest area analogously to the approach for the index values.

For the monthly analysis a total of 144 data points (18 years with 8 months each) was available for the correlation analysis (the applied data can be obtained from the authors on request). We restricted our analysis to the 13 non-city states (Fig.4.1) due to low shares of forest area in Berlin, Bremen and Hamburg. In addition to the monthly analysis, we have also tested the performance of the fire indices and meteorological variables against daily forest fire statistics for Brandenburg between 1993-2010. All fire indices and correlation coefficient (ρ) values were

obtained using programming language R (RDCT, 2009). Spatial data was processed with ArcGIS 9.2, ESRI.
We chose Spearman's ranked correlation test to evaluate the predictive power of both fire indices and raw input variables. This was determined by the fact that danger classes are ordinal, i.e. they are derived from unequal intervals (or ranges) of unclassified values and as such cannot be treated as continuous variables.

4.5 Results

Overall, correlation between the meteorological variables or fire indices and the number of fires is higher than for area burnt (Tab. 4.3 and Tab. A1 in supplementary material). For further analysis we concentrate on the correlation values obtained for the number of fires.

At the national level, relative humidity yields the highest median correlation coefficient value, respectively -0.7 (Fig. 4.2 and Tab. 4.3). Other meteorological variables considered show very low correlation values for number of fires, in general below 0.58 (obtained for maximum temperature). Among the different meteorological indices, the best combination of danger classes returned similar correlations as the mean for the indices M-68 (0.64 and 0.63), FWI (0.6 and 0.63) and Angström (0.61 and 0.62). Overall weaker correlations were found for the Baumgartner (0.59 and 0.57) and Nesterov (0.5 and 0.52) indices.

While the Angström, Nesterov and FWI indices achieve the best overall median performance when mean index values are considered, Baumgartner and M-68 Indices better explain observed fire patterns when danger classes 2 to 5 are used as an independent variables. We further investigate whether using the number of days below a certain threshold of relative humidity would improve the correlation with the number of fires. If monthly number of days with relative humidity below 70 % is used as independent variable, a maximum correlation coefficient of -0.72 is obtained (see Fig. A1 in supplementary material), which is only slightly higher as when mean monthly relative humidity is considered. We also tested the performance of the monthly minimum of relative humidity as a proxy for forest fire occurrence, however this leads to a lower correlation value of 0.69 (median of all states). Similarly, monthly maximum and mean values of unclassified indices (Angström, FWI and Nesterov) did not improve the correlation coefficient compared to the mean of classified values. We therefore focus on analyzing mean values of relative humidity and mean classified index values.

At state level, we find that correlation values can be highly diverging (Tab. 4.3). Regarding average relative humidity, correlation values for German states range between -0.39 for Saarland (SL) and -0.9 for BB. In fact, relative humidity alone was found to be the best proxy for the occurrence of forest fires in 9 of the 13 investigated states. Correlations were found to be stronger (above 80%) in typical fire prone states regarding the number of fires, namely: BB, SN, MV and ST, in deceasing order of correlation value. We found very low correlation values for the state of SL, which has, in absolute terms, the lowest number of fires per year in Germany. Finally, correlation coefficients for relative humidity at state level were found to be statistically different from the others at the 95% confidence level using the paired Wilcoxon T test. The monthly correlation between the meteorological variables and the forest fire indices with monthly number of fires for each state are significant in more than 90% of the cases.

The monthly distribution of number of fires, mean relative humidity and the best predictive fire index is shown in Fig. 4.3. Results refer to three federal states that historically present high number of fire occurrences, namely, BB, SN and ST. Regarding the number of fires, all three states show a sharp increase from March to April. Between April and August the level remains relatively constant in some cases with a slight increase in late summer such as in ST. From August to September a sharp decrease in average fire numbers is observed, denoting the end of the fire season. Mean relative humidity captures fairly well the above described yearly pattern of fire occurrences. The slight spring drop in relative humidity matches the increase in fire observations

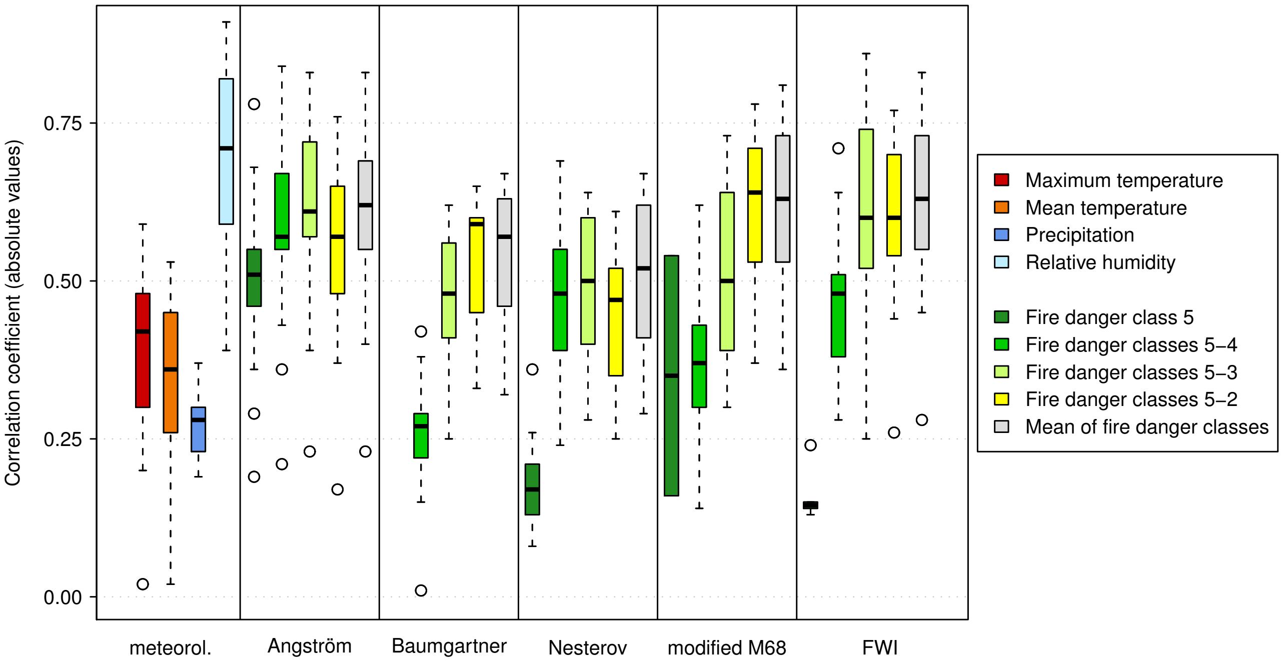

Figure 4.2: Boxplot of Spearman's correlation coefficients (ρ) (absolute values of coefficients) between monthly number of fires and meteorological variables as well as fire danger indices for 13 German Federal States from 1993 to 2010. In total, correlation values for meteorological variables and five investigated indices are shown. For each fire index we display the correlation ranges obtained with the mean monthly values and the different combinations of danger classes. In each box the horizontal line represents the median, the outer box the 25th and 75th percentiles, the whiskers either the maximum or 1.5 times the inter-quartile range. Outliers are marked by circles. The sequence of the boxes follows the same order as the legend description.

for all considered states and the mean relative humidity values remain rather constant until August, in line with the period when high fire activity is registered. By comparison, the pattern of fire risk obtained with the FWI (classes 3 to 5) rise sharply until May for BB and SN. In ST, FWI values increase monotonically until July and August, missing the sharp spring increase in fires.

The overall ability of mean relative humidity in describing monthly fire numbers raises the logical question whether the same holds in case of daily fire occurrences. In order to investigate such possibility, we have analyzed daily correlation values between the investigated set of independent variables and forest fire statistics for BB for the period 1993–2010. Correlations between daily meteorological variables and fire index class are now on par with those for area burnt (Tab. 4.4). This is in contrast to what was observed at the monthly level. The mean daily relative humidity (ρ =-0.62), together with the FWI and Angström (both ρ =0.63) indices provide the highest correlation values. Note that due to the differing aggregation level of monthly and daily analysis the absolute value of the correlation coefficients are not directly comparable. In a statistical sense, there is no difference between using relative humidity or the previous highlighted fire indices at monthly or daily scales in BB.

Table 4.4: Correlation coefficients of daily meteorological variables and index classes with daily number of forest fires and area burnt for the state BB. The fire data was directly correlated with the respective fire danger class. ρ values were significant at 95% confidence level.

	number of fires	area burnt
Tmax	0.49	0.47
Tmean	0.44	0.41
P	-0.28	-0.28
RH	-0.62	-0.62
Angström	0.63	0.61
Baumgartner	0.53	0.52
Nesterov	0.53	0.51
M-68	0.61	0.59
FWI	0.63	0.61

Table 4.3: Spearman's correlation coefficients (ρ) between monthly number of fires and meteorological variables as well as fire danger indices for 13 German Federal States from 1993 to 2010. Average classified index values are considered as well as number of days per month falling into different categories of danger classes. ρ values were significant at the 95% confidence level except for those in italics. The best performing approach (for ρ > 0.5) for each state is marked in dark grey, the second best in light grey. The numbers in brackets after the fire index abbreviation represent the range of danger classes included to perform the fit. NAs signify zero days with that danger class for the whole state.

	BW	BY	BB	HE	MV	NI	NW	RP	SL	SN	ST	SH	TH	Median
Tmax	0.2	0.3	0.59	0.31	0.42	0.44	0.28	0.48	*0.02*	0.52	0.51	0.35	0.47	0.42
Tmean	*0.16*	0.26	0.53	0.27	0.36	0.39	0.24	0.45	*-0.02*	0.48	0.46	0.33	0.42	0.36
P	-0.3	-0.19	-0.21	-0.31	-0.29	-0.37	-0.28	-0.27	-0.2	-0.29	-0.23	-0.25	-0.33	-0.28
RH	-0.48	-0.74	-0.9	-0.7	-0.82	-0.75	-0.7	-0.58	-0.39	-0.86	-0.8	-0.44	-0.69	-0.7
Ang.(5)	0.29	0.36	0.78	0.5	0.55	0.55	0.51	0.49	0.19	0.61	0.68	0.46	0.55	0.51
Ang.(4-5)	0.36	0.55	0.84	0.57	0.67	0.59	0.55	0.55	0.21	0.71	0.73	0.43	0.63	0.57
Ang.(3-5)	0.39	0.61	0.83	0.58	0.72	0.68	0.57	0.6	0.23	0.78	0.74	0.5	0.66	0.61
Ang.(2-5)	0.37	0.52	0.76	0.48	0.63	0.65	0.48	0.57	0.17	0.72	0.67	0.4	0.58	0.57
Ang. (av.)	0.4	0.58	0.83	0.57	0.69	0.69	0.55	0.62	0.23	0.77	0.73	0.45	0.65	0.62
Ba.(5)	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	NA
Ba.(4-5)	*0.15*	0.29	0.38	0.26	0.28	0.27	0.24	0.19	0.22	0.42	0.29	*0.01*	0.28	0.27
Ba.(3-5)	0.34	0.52	0.62	0.56	0.6	0.41	0.48	0.32	0.48	0.58	0.52	0.25	0.42	0.48
Ba.(2-5)	0.46	0.64	0.64	0.59	0.59	0.59	0.57	0.45	0.42	0.65	0.6	0.33	0.43	0.59
Ba. (av.)	0.44	0.65	0.67	0.62	0.62	0.57	0.57	0.42	0.46	0.67	0.63	0.32	0.46	0.57
Ne.(5)	0.18	0.2	0.36	0.24	0.17	*0.1*	*0.13*	*0.16*	0.21	*0.12*	0.26	*0.08*	*0.15*	0.17
Ne.(4-5)	0.37	0.41	0.69	0.49	0.48	0.48	0.39	0.51	0.24	0.56	0.62	0.36	0.55	0.48
Ne.(3-5)	0.38	0.4	0.64	0.5	0.6	0.58	0.4	0.48	0.28	0.63	0.59	0.43	0.64	0.5
Ne.(2-5)	0.34	0.35	0.53	0.41	0.52	0.54	0.37	0.47	0.25	0.61	0.49	0.34	0.51	0.47
Ne. (av.)	0.38	0.42	0.67	0.51	0.61	0.61	0.41	0.52	0.29	0.67	0.62	0.41	0.65	0.52
M-68 (5)	*NA*	*NA*	0.54	*NA*	*NA*	*NA*	*NA*	*NA*	*0.16*	*NA*	*NA*	*NA*	*NA*	0.35
M-68(4-5)	0.37	0.38	0.62	0.34	0.46	0.35	0.24	0.25	0.4	0.43	0.47	*0.14*	0.3	0.37
M-68(3-5)	0.33	0.51	0.73	0.5	0.64	0.52	0.39	0.33	0.41	0.65	0.65	0.3	0.44	0.5
M-68(2-5)	0.48	0.68	0.78	0.68	0.75	0.64	0.63	0.53	0.5	0.76	0.71	0.37	0.62	0.64
M-68 (av.)	0.49	0.69	0.81	0.7	0.75	0.63	0.63	0.53	0.5	0.77	0.73	0.36	0.63	0.63
FWI (5)	*0.15*	*NA*	*0.13*	*NA*	*NA*	*NA*	*NA*	*NA*	0.24	*0.14*	*0.14*	*NA*	*0.15*	0.15
FWI (4-5)	0.4	0.32	0.71	0.51	0.48	0.38	0.33	0.5	0.28	0.53	0.64	0.49	0.46	0.48
FWI (3-5)	0.44	0.59	0.86	0.6	0.74	0.65	0.52	0.59	0.25	0.79	0.76	0.52	0.63	0.6
FWI (2-5)	0.44	0.6	0.77	0.59	0.71	0.69	0.54	0.6	0.26	0.75	0.7	0.47	0.68	0.6
FWI (av.)	0.45	0.61	0.83	0.63	0.73	0.7	0.55	0.62	0.28	0.78	0.74	0.5	0.7	0.63

To test the robustness of the results based on the Spearman's ranked correlation test, we have additionally analysed the daily fire performance of Brandenburg with the ranked percentile curve (after Eastaugh et al., 2012) and the ROC curve (Receiver Operation Characteristic). For this, the data on daily fire occurrence was converted to a binary data set of presence and absence of forest fires. Again, relative humidity performs similarly well as other indices such as the FWI or the Angström index (for more information see supplementary material).

We further investigated future forest fire risk based on the identified best performing approaches. In Fig. 4.4 we therefore show the possible future shifts in fire risk according the proxies "mean relative humidity" (panels a and c) and "number of days with danger classes 2 to 5" given by the M-68 index (panels b and d). The projections show a consistent increase in risk for relative humidity independent of the considered scenario. The scenarios influence nevertheless the magnitude of changes (deviation from historical values). When all scenarios are considered, on average relative humidity will reduce by 1.2-3 % points in spring. In summer months, reductions between 2 and 4.8 % points are estimated (Fig. 4.4c). If the M-68 is used as proxy we obtain heterogeneous patterns of fire risk. For example, in the months of May we see a lowering in fire index values under all scenarios considered. For the remaining months of the year changes in fire index values are positive with a maximum deviation in July (an increase of 2 to 9.2 days belonging to danger classes 2 to 5). Independent of the scenario and proxy, the spring fire risk does not show a substantial deviation from historical values (see Fig. 4.4 c and d). Overall, the highest spring fire risk is

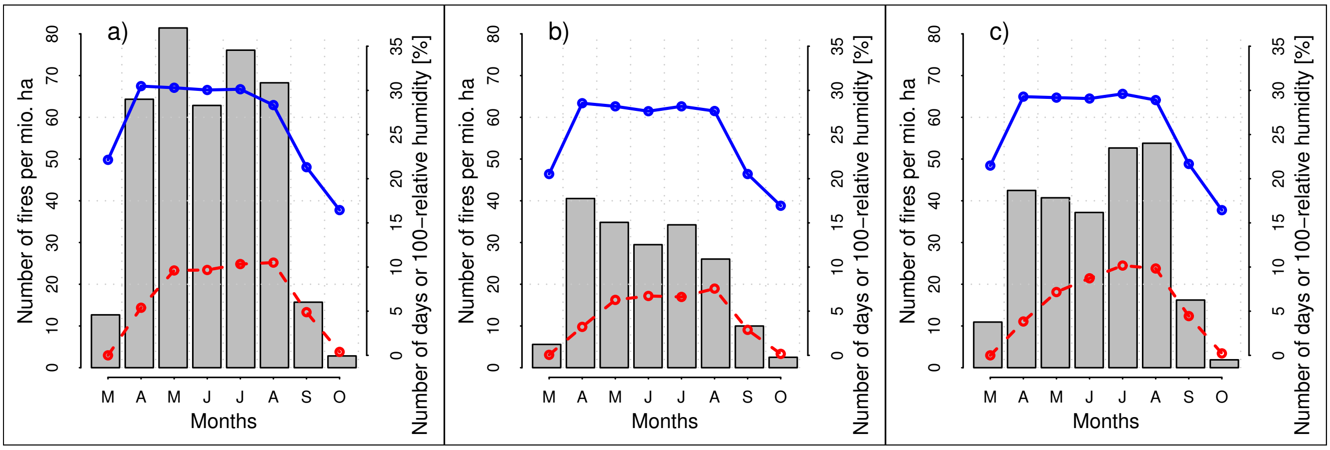

Figure 4.3: Observed monthly number of forest fires (grey bars), relative humidity values (blue continuous line) and number of days falling falling into the index classes 3-5 for the FWI (red dashed line) for the three most fire prone states a) BB, b) SN and c) ST. The right y-axis represents both the frequency of danger classes (days) and the relative humidity. Note that for better comparability with the indices and the observed fires, relative humidity values are reversely displayed, as the difference to 100%.

attained under a 2 K temperature increase and dry conditions, whereas a 3 K rise under medium moisture conditions leads to a stronger increase in summer fire risk. Further, the projections point to higher fire risk in March and October, particularly according to relative humidity, thus prolonging the potential fire season.

4.6 Discussion

We evaluated five meteorological forest fire indices and four meteorological variables regarding their predictive performance for Germany at state-level on a monthly basis. We also tested their performance on a daily basis for the state of BB. These indices have not been compared for Germany on a monthly scale before. Also, there was a lack of a comprehensive comparison of their performance against meteorological input variables. However, such an analysis is essential to justify the application of these indices some of which are quite complex comprising many parameters.

Relative humidity demonstrates a predictive power comparable to the investigated indices in the daily analysis and a superior power for most of the states in the monthly analysis. It is plausible that relative humidity in itself is a good indicator of fire conditions and occurrence as it indirectly includes information concerning temperature, precipitation and biophysical processes of the surroundings – in accordance with Wittich (1998) and Skvarenina et al. (2004). We have identified a lack of substantial improvement in the explanatory power of the fire indices when compared to the capacity of relative humidity alone in describing observed fire patterns. This was true both at monthly and daily time scales in Germany and BB respectively.

The fact that fire indices do not stand out regarding their explanatory power during the monthly analysis is intriguing. This is surprising, since the indices here evaluated incorporate relative humidity either directly in their equations (eg. Angström Index) or indirectly in order to derive auxiliary parameters (e.g. dew point temperature calculation in the Nesterov index). On a daily basis, the performance of fire indices FWI, M-68 and Angström are on par with the results obtained with relative humidity (see Tab. 4.4). Among the indices, the modified M-68 used by the German Weather Service showed the best overall performance at a monthly scale. This is in line with results for the severe forest fire year of 1975, where the M-68 Index provided better results than the Baumgartner Index, regarding the reproduction of the observed daily pattern of burnt area (Wittich, 1998). However, we found that the FWI adapted to European conditions constitutes a valid alternative to the

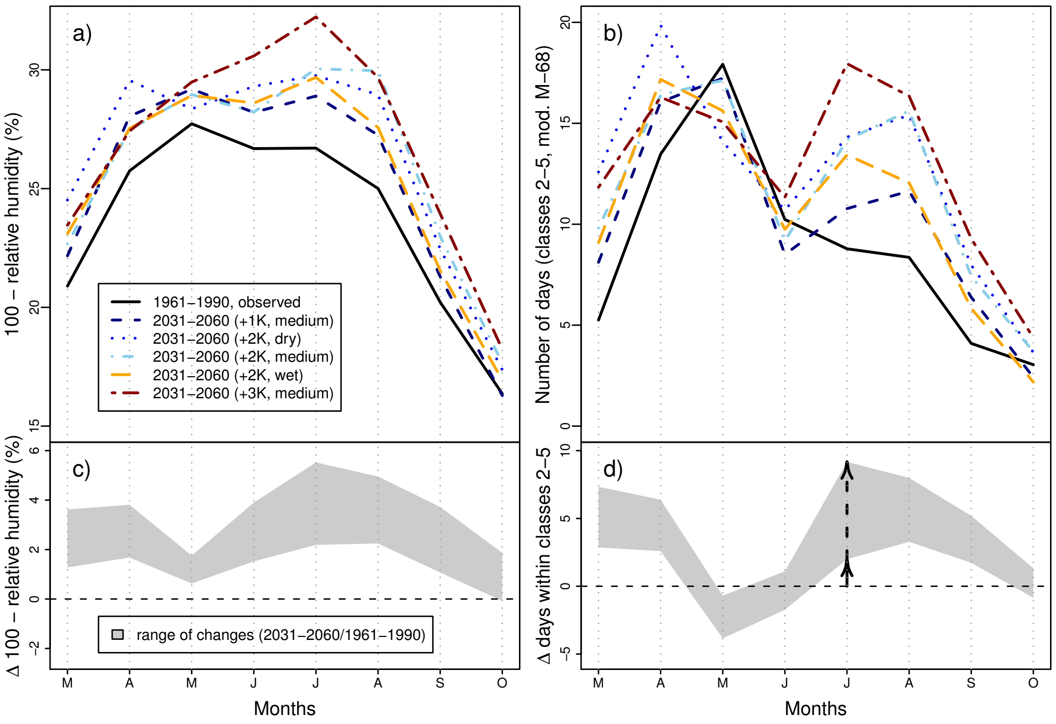

Figure 4.4: Observed values of relative humidity (left panels) and the modified M-68 index (right panels) averaged over all states between 1961-1990 (black solid line) and projected values of the model STAR for different temperature and moisture scenarios (dashed colored lines). Note that for better comparability with the indices and the observed fires, relative humidity values are reversely displayed, as the difference to 100 %. For the modified M-68 index, all days falling into classes 2-5 were considered. Panels c and d display the difference between the observed monthly values regarding lowest and highest changes as projected according to the different scenarios. For example according to the modified M-68 model, days of fire risk will increase by 2 (moderate scenario) to 9.2 days (extreme scenario) in July (see black arrow in panel d). Inserted legends on the left panels refer equally to the panels on the right.

M-68 in the most fire prone states. At daily scales for the state of Brandenburg, it seems that relative humidity, the FWI, the modified M-68 or the Angström index are equally valid descriptors. The potential of relative humidity to outperform established forest fire indices has already been documented. For example, Padilla and Vega-García (2011) shows a substantial heterogeneity of independent variables in explaining fire statistics across 53 eco-regions in Spain: minimum relative humidity outperformed FWI - as well as several fuel moisture models - as the main explanatory variable of a logistic regression for large regions of the country. Skvarenina et al. (2004) also stresses the sensitivity of fires to relative humidity for Slovenia. The importance of relative humidity has been previously highlighted also for Germany (Wittich, 1998). For example, during the extreme years of 1992 and 1993 most fire occurrences have been recorded in days with relative humidity ranging from 40 to 15% (Lange, 1994). Hence, our results reinforce the spatial heterogeneity of fire predictors and the important role of relative humidity.

Our approach has some limitations. Not all input variables required in fire indices calculation were directly available and have been approximated by means of other meteorological variables (e.g. mean relative humidity correction to minimum relative humidity) or empirical models (e.g. phenology dates). Nevertheless the effect of some approximations (e.g. snow days) can be considered as minor during the fire season. Even assuming that correlations obtained with fire indices improve when original input data rather that our approximations is used (see Tab. 4.2), it remains questionable to what extent correlations would substantially improve beyond the values obtained with relative humidity alone, e.g., -0.9

BB, -0.86 SN, -0.82 MV and -0.8 ST. Similar to what has been observed at European level (JRC-IES, 2006), we cannot exclude the effect of differences in fire reporting between German states, especially in regions where forest fires are rare – for example Saarland. Further research could investigate in more detail the influence of the classification scheme of the index values on the performance results, which we have analyzed for three of the five selected indices. Finally, we neglected feedbacks between biosphere and atmospheric conditions for the projection of fire risk. The patterns of vegetation are relevant and have been found to influence the occurrence of future fires. Thonicke and Cramer (2006) used the Regional FIRe Model (Reg-FIRM) embedded in a global vegetation model to study long-term trends in vegetation dynamics and forest fires for BB. They expect that fire risk could be contained within historical levels if the proportion of needle-leaved forests is reduced to at least 50%.

The results from our projections show a considerable increase in summer fire risk, especially when M-68 index is used a proxy for fire occurrence. Spring fire risk also increases but by a smaller amount across all considered scenarios. An increase in summer fire risk is also noted by Camia (2008) in a similar projection of forest fire risk using FWI run on the HIRHAM index for Europe. Their projections for the period 2071–2100 confirm a higher increase for June, July and August than for March, April and May for the IPCC SRES high emissions A2 climate change scenario.

Finally, the ability of relative humidity to describe current monthly patterns of forest fires raises the question to what extent projections of future fire risk for Germany should be based solely on existing indices.

4.7 Conclusion

In Germany, monthly occurrence of forest fires was found to be conveniently described by variations of relative humidity alone. This was consistent for most of the German states investigated. Commonly used fire indices (including two specifically tailored for Germany) did not improve the explanatory power for number of fires or area burnt obtained with relative humidity alone. This raises the question on the suitability of more complex indices – which often include this meteorologic variable in their formulation – for Germany. When investigating fire occurrences on a daily basis for BB, the performance of relative humidity was comparable to the FWI or the modified M-68. We assume that the good performance of relative humidity is due to its integrative nature, which is related to the atmospheric moisture content than in turn is known to influence the moisture level of surface litter.

Historically, two distinct fire periods were characteristic for Germany, in spring and in summer with medium risk period in June. Projections suggest a strong increase in the summer fire risk and a possible extension of the fire period to February and November, which are presently not considered months of high fire risk. This also means that the indices which are based on certain dates regarding the vegetation period, may need to be tested and optimized for potentially different climatic conditions in future. Other indices, such as the Baumgartner, appear to be not suitable under changing climatic conditions, since fire risk classes are based on fixed monthly corrections.

The apparent robustness of relative humidity in describing past fire events in Germany supports the idea that even simpler predictive models with lower degrees of freedom are possible. This is especially relevant for regions with limited availability of climatic data. Thus, following the principle of Occam's razor, the simpler method is more favorable in this context. This also enhances the application of forest fire warning systems in the practical field and in modeling approaches. However, more research is necessary to investigate these relationships for other regions and different spatial and temporal scales.

5

Assessment of climate change impacts on soil moisture dynamics in Brandenburg*

Abstract

Global warming impacts the water cycle not only by changing regional precipitation levels and temporal variability, but also by affecting water flows and soil moisture dynamics. In Brandenburg, increasing average annual temperature and decreasing precipitation in summer have already been observed. For this study, past trends and future effects of climate change on soil moisture dynamics in Brandenburg were investigated, considering regional and specific spatial impacts. Special Areas of Conservation (SACs) were focused on in particular. A decreasing trend in soil water content was shown for the past by analyzing simulation results from 1951 to 2003 using the integrated ecohydrological model SWIM (Krysanova et al., 1998). The trend was statistically significant for some areas, but not for the entire region. Simulated soil water content was particularly low in the extremely dry year 2003. Regionally downscaled climate change projections representing the range between wetter and drier realizations were used to evaluate future trends of available soil water. A further decrease of average available soil water ranging from -4% to -15% was projected for all climate realizations up to the middle of the 21st century. An average decrease of more than 25mm was simulated for 34% of the total area in the dry realization. Available soil water contents in SACs were generally higher and trends in soil moisture dynamics were lower mainly due to their favorable edaphic conditions. Stronger absolute and relative changes in the simulated trends for the past and future were shown for SACs within Brandenburg than for the state as a whole, indicating a high level of risk for many wetland areas. In a subsequent analysis, the potential for a reduction in the complexity of the model based on the simulated values is explored. For this, they key input variables to explain the simulated soil water levels are identified.

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5.1 Impact of climate change on soil moisture dynamics in Brandenburg with a focus on nature conservation areas

5.1.1 Introduction

Soil moisture is a key component of the hydrological cycle, controlling the partitioning of precipitation between runoff, evapotranspiration and deep infiltration (Daly and Porporato, 2005). As a link between the biosphere and the edaphic zone, soil water plays a crucial role for terrestrial ecosystems by determining plant growth. If the soil water level falls below a species-specific threshold, plants experience water stress, and decreased soil moisture under warmer conditions can inhibit photosynthesis (Lindroth et al., 1998).

Various feedbacks between soil moisture and the biological and hydrological cycles exist. For example, vegetation can influence the soil water regime by offsetting drier conditions through decreased transpiration, a phenomenon which is expected to occur more frequently in summer months under a warmer climate (Etchevers et al., 2002; Seneviratne et al., 2002; Yang et al., 2003). In addition, dry soils can cause a negative feedback by amplifying the impact and duration of heat waves (Brabson et al., 2005) and prolonging the effects of meteorological droughts (Nicholson, 2000). The exceptionally hot summer of 2003 in Europe led to large-scale soil moisture depletion and associated ecosystem impacts (Reichstein et al., 2007). If average soil moisture conditions had been maintained in the spring and summer of 2003, then summer heat anomalies would have been about 40% less severe in some regions of Europe (Fischer et al., 2007).

Long-term historical soil moisture records of in situ observational data or estimates derived from remote sensing are available only for a few regions (Trenberth et al., 2007). Examples of studies based on such data have shown significantly decreasing trends in soil moisture in recent decades for Eastern Hungary (Makra et al., 2005), and an increasing trend in recent decades for Ukraine (Robock et al., 2005).

Future projections on soil moisture are represented by only a few studies. For example, Gerten et al. (2007) concluded a global scale decline in soil moisture for many regions up to 2100. This does not necessarily mean that ecosystems are water-limited, as this model assumes increasing water-use efficiency in plants under increasing CO_2 levels. Projections for the regional scale using models require downscaling of climate scenarios (Seneviratne et al., 2002; Bronstert et al., 2003). Expected climate change could generally lead to decreased soil water content in the United Kingdom (Naden and Watts, 2001), and a strong decrease in soil moisture in summer in Switzerland (Jasper et al., 2006) and Southern Europe (Gregory et al., 1997). Etchevers et al. (2002) analyzed the impact of climate change on the Rhone river catchment, finding strong regional variations in simulated soil moisture changes. Naden and Watts (2001) studied future soil moisture changes in areas of ecological interest in the UK, but with a single vegetation type and a limited number of soil types. Larger changes in soil moisture were found for soils with higher clay content. A very fine spatial resolution was applied by Jasper et al. (2006) for soil water analysis in the Thur river basin in Switzerland. They limited the study to a few soil types and concentrated on changes in the summer months. Smaller changes in available soil water were shown for sandy soils compared to clay soils and for forests compared to grasslands or farmland.

The present study aims at investigating past and future trends in soil water dynamics in the Federal State of Brandenburg (Fig. 5.1), Germany, from 1951 until 2055. The case study area was chosen because it is characterized by relatively dry conditions and predominantly sandy soils (Landgraf and Krone, 2002), and is considered to be one of the most vulnerable regions to climate change in Germany as regards nature and biodiversity conservation, agriculture, forestry and water availability aspects (Zebisch et al., 2005). The study aimed to carry out an area-wide analysis of past and future soil water changes in the State of Brandenburg, and used the regional ecohydrological model SWIM (Krysanova et al., 1998), which considers major vegetation and soil types with a high spatial resolution. SWIM is particularly suited for this analysis since it offers flexibility of spatial resolution, incorporates both hydrological and ecological processes and it has been successfully applied in various studies analyzing hydrological dynamics in the Elbe basin and Brandenburg (Hattermann et al., 2005; Krysanova et al., 2005; Post et al., 2007; Wattenbach et al., 2007). Trends in simulated soil moisture were compared to trends in average annual values of the Palmer Drought Severity Index (PDSI). Thus simulated soil moisture results could be compared with those produced by an independent method of analyzing drought severity. Furthermore, the impacts for different soil and vegetation types were analyzed. Particular emphasis in this study was given to Special Areas of Conservation (SACs) as defined by the EU Habitats Directive (92/43/EEC) in order to assess the spatially explicit risk for targets of this directive concerning these areas, which are of particular ecological and conservational value. Simulated soil water values for the whole area of the state were compared to results obtained for the SACs.

5.1.2 Methods

Case study area

Brandenburg is characterized by a relatively low average annual precipitation, below 600mm in the period 1951-2000 (Gerstengarbe et al., 2003), and a dense network of rivers and streams (Landesumweltamt Brandenburg, 2006). The spatial differences in average annual temperatures range from 7.8 °C to 9.5 °C in this time period (Gerstengarbe et al., 2003), while precipitation values range from below 500mm in the north-east to over 600mm in the south-west and north-west. More than half of Brandenburg is covered by poor sandy soils. About half of the area is used for agricultural production, and about a third for forestry, with pine trees being the dominant species (Landgraf and Krone, 2002).

The protected areas considered in this study, so called SACs, comprise 620 sites in Brandenburg in total (Fig. 5.1), representing about 11.3% of the states area (Landesumweltamt Brandenburg, 2006). Brandenburg has one of the largest shares of wetlands of all German states, most of which are under agricultural use (Landesumweltamt Brandenburg, 2006). Many of these wetlands have already been negatively impacted by regional water shortages with decreasing water levels in ground water, water bodies and fenlands (Landgraf and Krone, 2002). A pilot study showed that Brandenburg is characterized by biotopes with a large share of species adapted to wet and cold conditions due to the relatively large area of fenlands (Holsten, 2007). These species have a high conservation value but could be severely affected by the expected climate change.

Climate change is already being observed in Brandenburg. A notable regional warming of 1K in recent decades compared to 0.7K on a global scale has been recorded (Lahmer and Pfützner, 2003). A trend towards a decrease in annual rainfall has been noted in Brandenburg in the last few decades, together with a trend towards a shift in precipitation from summer to winter (Bronstert et al., 2003). The climatic water balance (the difference between precipitation and potential evapotranspiration) is negative, and it is expected to become even more negative by 2055, leading to a decrease in groundwater recharge (Bronstert et al., 2003; Gerstengarbe et al., 2003).

The SWIM model

The ecohydrological model SWIM (Soil and Water Integrated Model) (Krysanova et al., 1998, 2000) is a continuous-time spatially semi-distributed model simulating hydrological processes, vegetation growth, nutrient cycling (carbon (C), nitrogen (N) and phosphorus (P)) and sediment transport at the river basin scale. SWIM simulates all processes by disaggregating the basins to subbasins and hydrotopes, where the hydrotopes sets of elementary units in a subbasin with the same soil and land use types are the highest disaggregated units. Up to 10 vertical soil layers can be considered for hydrotopes. It is assumed that a hydrotope behaves uniformly regarding hydrological processes and nutrient cycles. The spatial disaggregation scheme in the model is flexible. In regional studies climate zones, grid cells of a certain size, or other areal units can be used for disaggregation of a region instead of subbasins.

Water flows, nutrient cycling and plant growth are calculated for each hydrotope. Then lateral fluxes of water and nutrients to the river network are simulated, taking retention into account. Lateral flows between hydrotopes are not simulated

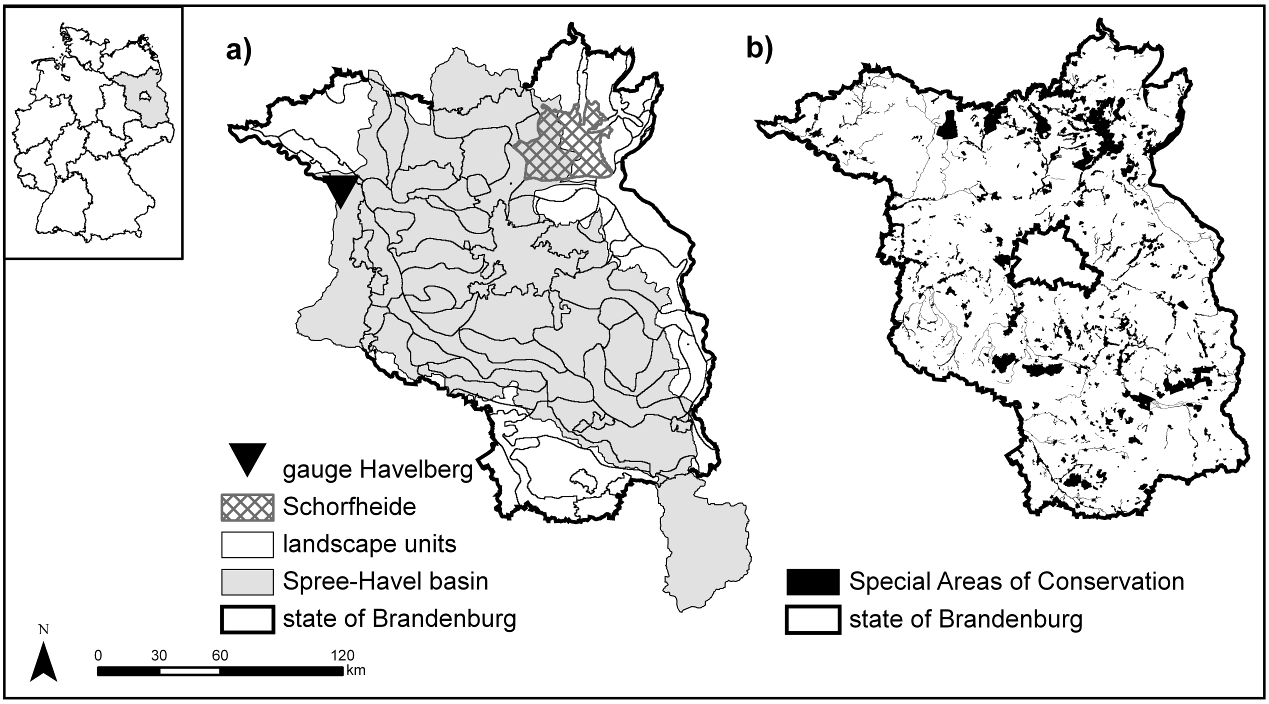

Figure 5.1: (a) Location of the SpreeHavel basin with the corresponding gauge Havelberg together with the landscape units and the selected unit Schorfheide. (b) Special Areas of Conservation (SACs) within Brandenburg.

in this regional scale model. After reaching the river system,water and nutrients are routed along the river network to the outlet of the simulated basin. The soil root zone is subdivided into several layers in accordance with the soil database. The water balance for the soil surface and soil column includes precipitation, surface runoff, evapotranspiration, subsurface runoff and percolation. Surface runoff is estimated as a non-linear function of precipitation and a retention coefficient depending on soil water content, land use and soil type (modification of the Soil Conservation Service (SCS) curve number method) (Arnold et al., 1990). Lateral subsurface flow is calculated when the storage in any soil layer exceeds field capacity after percolation. Potential evapotranspiration is estimated using the PriestleyTaylor method (Priestley and Taylor, 1972).

The module representing crops and natural vegetation is an important interface between hydrology and nutrients. A simplified EPIC approach (Williams et al., 1984) is included in SWIM for simulating arable crops and aggregated vegetation types, using specific parameter values for each crop and vegetation type. A number of plant-related parameters are specified for the crop and vegetation types in the database attached to the model. Vegetation in the model affects the hydrological cycle by the cover-specific retention coefficient, impacting surface runoff, and indirectly influencing the amount of transpiration. The latter is simulated as a function of potential evapotranspiration and leaf area index (LAI).

The model has proven to be able to adequately reproduce observed hydrological characteristics (river discharge and groundwater table) in mesoscale and large basins (Krysanova et al., 1998; Hattermann et al., 2002, 2004; Yu et al., 2009). Comparison of simulated soil water with measured data for three field sites in Brandenburg and neighboring states showed an overall reliable representation of the temporal dynamics and magnitudes of soil water contents for different soil depths (Post et al., 2007).

Statistical methods

Trend analysis was performed using an advanced MannKendall (MK) non-parametric test (Mann, 1945; Kendall, 1975) proposed by Yue et al. (2002). This test allows serial correlation of the data to be taken into account, as positive serial correlation usually leads to a greater tendency to reject the null hypothesis of no trend. After detrending the time series using the Theil and Sen approach (Theil, 1950; Sen, 1968), the significance of serial autocorrelation was tested using the equation of Salas et al. (1980). This method was applied to detect trends in average annual soil moisture for each of the 3326 hydrotopes for the period 1955-2003. Since only 10 of 3326 detrended time series showed significant serial correlation, it was ignored, and the original MK test was used. The p-values equal or lower than 0.05 indicate statistically significant trends at the 5% level, and the p-values larger than 0.05 indicate insignificant trends.

Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI) (Palmer, 1965) was used in the study to compare patterns of negative trends in soil moisture with patterns of negative trends in PDSI. This index was developed based on the supply-and-demand concept of the water balance equation which was used in the study. The PDSI is calculated based on monthly average precipitation and temperature data, and taking into account the locally available water content (AWC) of the soil. The method determines all basic components of the water balance, such as evapotranspiration, water recharge, runoff and soil moisture in the surface layer. This hydrological index is used broadly in many applications worldwide.

The PDSI was calculated for spatial units representing uniform landscape units and soil types using climate data interpolated from 83 climate stations in Brandenburg in the period 1951-2003. For the estimation of the PDSI, in addition to meteorological data, data on available water capacity (AWC) of soils was used. The monthly PDSI values were calculated for every unit, and the average annual PDSI values were used for the trend analysis.

Since the PDSI for a subsequent month is dependent on the PDSI of the current and previous months, the errors from a simple regression model are unlikely to be independent. Therefore, the autocorrelation of the calculated time series was analyzed in advance with the function ar() from the R software package nlme and the generalized least square (GLS) function gls() was used including the obtained autoregressive order.

Table 5.1: Names of dominant soil types of Brandenburg and their corresponding soil type number according to the BÜK 1000.

Num.	**Soil type name**
6	Eutric histosols
8	Fluvisols/gleysols from loamy to clayey fluviatile sediments
12	Gleysols from sandy sediments of the ice-marginal valleys and lowlands
17	Haplic podzols/cambic podzols/gleyic podzols from sandy fluviatile sediments
19	Haplic luvisols/eutric podzoluvisols/stagnic luvisols from boulder clay
26	Dystric podzoluvisols/luvic arenosols/dystric cambisols from sandy sediments overlying boulder clay
27	Calcaric and umbric regosols/luvic arenosols from sandy to loamy end moraine deposits
28	Spodo-stagnic cambisols/stagnic podzoluvisols from loamy to sandy deposits overlying boulder clay
29	Stagnic and spodic gleysols from sandy deposits overlying boulder clay
31	Cambic podzols/spodic arenosols from dry dystrophic sand deposits
32	Eutric cambisols/luvic arenosols from eutrophic sand deposits
71	Soils redeposited by man and large open-cast mines (cumulic anthrosols)

Hydrological and climate data

Observation data provided by the German Weather Service (DWD) for the period 1951-2003 from 83 climate stations in and around Brandenburg were used as a climatic reference. The regional climate scenario for the period up to 2055 was created by the Climate group at PIK using the regional statistical downscaling model STAR (Werner and Gerstengarbe, 1997; Orlowsky, 2007). A regional temperature scenario was taken from the GCM ECHAM 5/MPI-OM (Roeckner et al., 2003) corresponding to the A1B scenario (Nakicenovic et al., 2000). STAR is a statistical downscaling model which re-samples observed data of climate stations through a cluster analysis using temperature trends as an input. STAR produced 100 stochastic realizations of regional climate for the period 2004-2055 based on the ECHAM scenario, with a higher uncertainty for precipitation than for temperature.

Three of these 100 realizations were selected for this study. Since the differences in the temperature of the realizations are relatively small, only precipitation was selected as the differentiating climatic parameter. Thus, three realizations were selected which reflected comparatively wet, medium and dry trends for Germany. Observed and scenario data for the climate stations were then interpolated to the centroids of the landscape units by the inverse distance method. Climatic inputs required by SWIM are daily precipitation, air temperature (maximum, average, and minimum) and solar radiation. Summer is represented by the months from July to September.

River discharge values from 1955 to 2000 were used from the gauge at Havelberg (Fig. 5.1a), provided by the Federal Institute of Hydrology (Bundesanstalt für Gewässerkunde).

Spatial data and model implementation

The Digital Elevation Model (DEM) used in this study has a 25m resolution and was supplied by the State Land Survey Office (Landesvermessungsamt Brandenburg). The biotope map with over 500 vegetation types was obtained from the State Environmental Agency (Landesumweltamt Brandenburg). The biotopes were aggregated to 15 land use categories of SWIM (Krysanova et al., 1998). The categories water and urban land categories were not considered in this study, intensive grassland and extensive grassland were aggregated to give the category grassland. Thus 10 land use types were considered in total. The category evergreen forest is hereafter referred to as coniferous to better account for the regional vegetation. Cropland is here represented by winter wheat as one of the major crops in the study area. This generalization seems acceptable, since a sensitivity study of simulated river discharge to model parameters of SWIM for a basin within the state of Brandenburg showed changes in the dynamic of discharge, but small total changes for different crop types (Krysanova et al., 2000).

The implemented soil map has a spatial scale of 1:1,000,000 (BK 1000), with geophysical soil parameters for 72 soil types. The map was provided by the National Agency for Geo-sciences and Resources (Bundesamt für Geowissenschaften und Rohstoffe). This soil data has already been parameterized for the model SWIM and been widely used in its application, thus allowing a comparison between studies. The soil map gives a total number of 18 soil types for the study area with 12 dominant ones (see Table 5.1), which, together with the 10 considered land use types, provide an adequate resolution for this regional analysis. The spatial data for the SACs was obtained from the Federal Agency for Nature Conservation (Bundesamt für Naturschutz) in Germany and is shown in Fig. 5.1b.

In this study the so-called landscape units after Gharadjedaghi et al. (2004) (see Fig. 5.1a) were used instead of river sub-basins to better account for the edaphic and vegetational patterns of the landscape. The landscape units were delineated by geomorphological as well as conservational criteria. The hydrotopes, as the spatial entity for the hydrological simulation, were identified within the landscape units by overlaying the landscape units (defining the climate parameters) with the land use and soil map using ArcGIS 9.1 by ESRI. Thus, a total number of 3326 hydrotopes was obtained for the study area with a unique combination of soil and land use information within the different landscape units.

After calibration, SWIM was run for all hydrotopes in Brandenburg for the period 1951-2003 using observed climate data, and for three realizations of the climate scenario (medium, wet and dry) for the period 2004-2055. Due to the starting phase of the model, the first 4 years of each run were not taken into account for the analysis. When comparing past and future values, the time periods 1961-1990 and 2046-2055 were used.

Actual available soil water for plants (in mm) was calculated for the upper 100 cm of soil profile of each hydrotope. As all soil types in the study area are parameterized to a depth of over 100 cm, the simulated soil water values allow comparisons to be made between the soils. For spatial presentation of the results, the simulated values were assigned to the generated map of hydrotopes.

Since the study area consists of more than 3000 hydrotopes, a selection for detailed analysis was made using the following two criteria: dominant hydrotopes in the study area and in the protected

Table 5.2: Precipitation and temperature change (1961-1990 compared to 2046-2055) of the chosen realizations in Brandenburg. The corresponding values for the landscape unit Schorfheide are shown in brackets.

Realiz.	Annual prec. change (mm)	Prec. change in summer (mm)	Annual temp. change (K)
Wet	+69 (+42)	+17 (+5)	+2.8 (+2.9)
Medium	-46 (-56)	-9 (-26)	+2.7 (+2.7)
Dry	-97 (-134)	-45 (-57)	+2.5 (+2.5)

areas were chosen, together with potentially interesting hydrotopes from a conservational perspective. For the latter reason, two wetlands and a potentially drier heathland hydrotope were chosen for comparison. The dominant hydrotopes in Brandenburg are cropland or coniferous forest on sandy soils. The most common ones in the SACs are represented by deciduous or coniferous forest on sandy soils and intensive grassland on a boggy soil. To ensure better comparison between the selected hydrotopes, they were selected from one specific landscape unit, which is characterized by a uniform climate in the model simulations. Here, the landscape unit Schorfheide was chosen (Fig. 5.1a), which has a relatively large area of SACs and is characterized by a comparatively strong decrease in precipitation in the considered climate scenario compared to the whole of Brandenburg (Table 5.2). Other relevant climatic parameters of Schorfheide and of Brandenburg are also shown in Table 5.2. The dominant soil types and vegetation groups of the unit Schorfheide are sandy soils under forest and cropland. The selected hydrotopes are listed in Table 5.3.

Table 5.3: Selected hydrotopes of the landscape unit Schorfheide with their corresponding soil and vegetation types.

Reason for selection of hydrotope	Vegetation type name	Soil type
Common in Brandenburg	Cropland	26
		12
Common in Brandenburg and SACs	Coniferous forest	31
Common in SACs	Grassland	6
	Deciduous forest	27
Interesting hydrotopes for conservation	Wetland forested	6
	Wetland non-forested	6
	Heather	31

5.1.3 Results

Model calibration and validation

Havelberg, representing the Havel basin with an area of 24,297 km^2. The administrative region of Brandenburg and the river catchment area do not precisely coincide; 78% of the river basin overlaps with the area of Brandenburg, and 63% of Brandenburg belongs to the basin (Fig. 5.1a). Calibration of discharge was carried out for the period 1955-1965. The time period 1971-2000 was subdivided into three decades for validation. The following parameters were used to calibrate the model: an evapotranspiration correction factor, three parameters describing snowmelt, a correction factor for saturated hydraulic conductivity, an alpha factor (reaction factor for groundwater), an initial level for groundwater and a correction factor for river routing. The Nash and Sutcliffe efficiency (Nash and Sutcliffe, 1970) and deviation in water balance (or volume error) were used to evaluate the models performance.

The obtained efficiency of 0.78 and -1% deviation in the water balance for the calibration period are comparable to values found in other studies. For example, Hattermann et al. (2006) obtained a Nash-Sutcliffe efficiency of 0.7 for the calibration period and 0.54 for the validation period for the river Nuthe, which is a part of the Havel basin. For three decadal periods from 1965 to 1994, the efficiency was 0.81, 0.78, and 0.67-0.81, and deviation in water was +2%, +4% and +18%, respectively. The results (Fig. 5.2) are satisfactory, especially when taking into account that the Havel is a lowland river with extensive water regulation (drainage networks, irrigation,water supply for the Berlin metropolitan area, and lignite-mining-related water management), which was changing during this period of time.

One possible reason for the higher volume error for the last decade 1985-1994 is the influence of

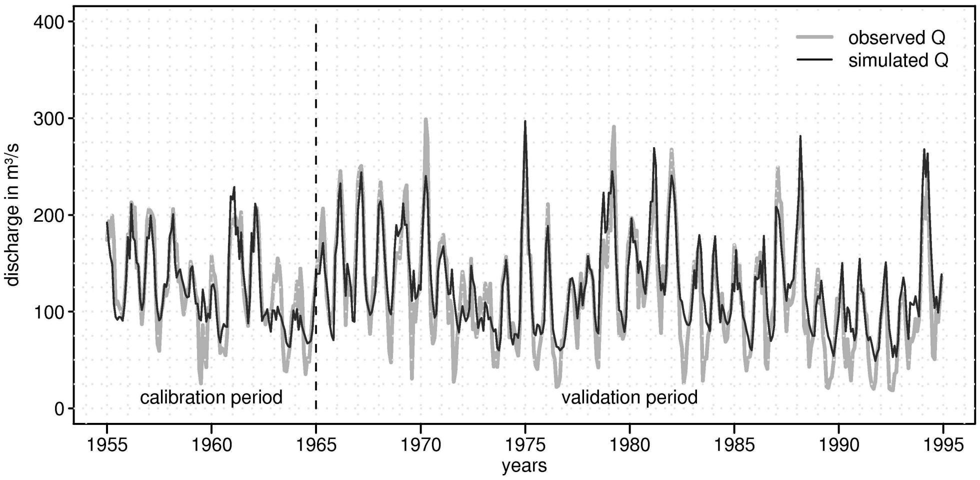

Figure 5.2: Comparison of observed and simulated water discharge (Q) at Spree-Havel basin outlet gauge Havelberg.

water use for irrigation with its peak in the late 1980s. According to the published data, the irrigation area of Brandenburg in 1995 was about 20,000 ha (Albrecht, 2003). An additional simulation experiment with SWIM for the 1980s demonstrated that the deviation in the water balance of +9% in the period 1981-1990 would be reduced to +5% taking into account irrigation with a water use of 100mma^{-}1 for an area of 20,000 ha in summer months. Unfortunately, more detailed irrigation data for the whole period were not available.

Soil water trends in Brandenburg

Overall, there was a negative trend in average annual available soil water content for the observation period 1955-2003 (Fig. 5.3). There are practically no trends for the medium (p = 0.58) and wet realizations (p = 0.99) of the climate scenario, but a negative and statistically significant trend for the dry realization (p = 0.01).

The spatial distribution of the average available soil water in the period 1961-1990 (Fig. 5.4) shows high available soil water contents of over 225mm in the Oder river floodplains in the east and in the Elbe and Havel river floodplains the north-west. Dry conditions with water content below 75mm dominate in the Uckermark district in the north-east of Brandenburg. During the exceptionally warm summer of 2003, soil moisture decreased considerably over the whole region by an average of 20mm compared to the average values for 1961-1990 (Fig. 5.4b).

Even under higher precipitation conditions in the wet realization, a general decrease (-6mm on average) in annual available soil water is expected for the mid 2050s compared to 1961-1990 (Fig. 5.4c). This could mainly be caused by increased evapotranspiration under a warmer climate. A study for the Elbe basin, in which large parts of Brandenburg are situated, showed that evaporation has a strong influence on the landscape water balance (Hattermann et al., 2007). Temperature and radiation were identified as the main drivers of this process. An increase in available soil water of over 5mm for the wet realization was found for the floodplains of the river Oder and for some parts of the Elbe-Elster plains in the southwest. However, a strong decrease (-21mm on average) for the almost entire area was simulated for the dry scenario realization (Fig. 5.4d). The most pronounced decrease was projected for floodplains of the rivers Oder, Elbe, Havel and Spree with grassland and cropland on fluvisols or histosols.Adecrease of more than 25mm was simulated for 34% of the total area.

Comparison with the drought index

The trends of average annual PDSI are significant ($p \leq 0.05$) for most of the area (Fig. 5.5a). Comparing patterns with a significant trend in PDSI

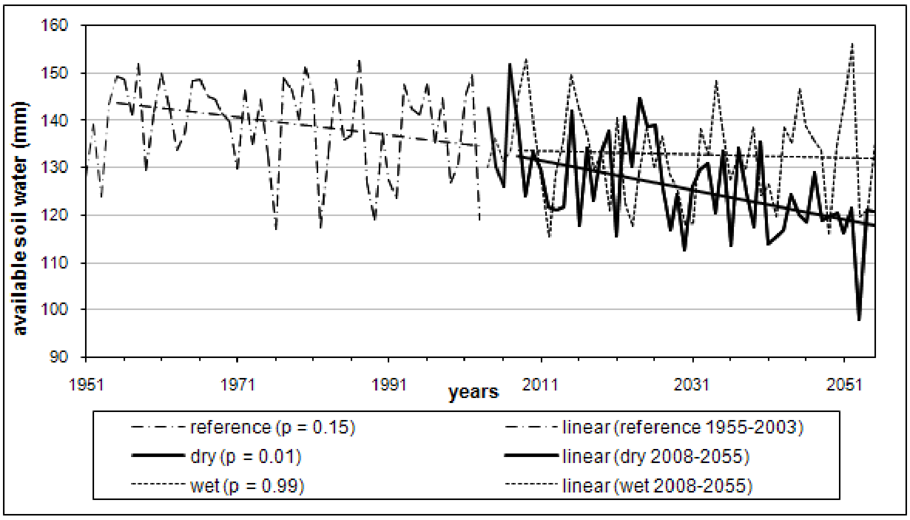

Figure 5.3: Trend of available soil water in Brandenburg from 1951 to 2055 for the reference period and two realizations.

with patterns of trends in simulated available soil water for the same period (Fig. 5.5b) revealed some similarities. Generally, the patterns of the strongest trends in available soil water (red areas south of Berlin in Fig. 5.5b) coincide with the pattern of a strongly significant trend in PDSI ($p \leq 0.01$). Also areas with a small negative trend or no trend in soil water content to the east of Berlin (green and yellow areas in Fig. 5.5b) match with patterns of insignificant trends in PDSI. This represents an independent validation of the results obtained by the SWIM model.

Trends for selected hydrotopes

In addition, trends in available soil water were analyzed for some selected hydrotopes (Table 5.3). The levels of simulated available soil water content differed significantly, from over 140 to 200mm for histosol (6) to lower than 120mm for cambic podzol (31) and dystric podzoluvisol (26) (Fig. 5.6). Interannual variability differed considerably between hydrotopes. The hydrotopes on histosol (6) showed a much higher variability compared to the hydrotopes on cambic podzol (31). Simulated soil water content in forested wetland on histosol (6) was lower than in non-forested wetland and grassland on the same soil. This is probably due to the higher transpiration in forest.

In five cases out of eight, trends were statistically significant in the period of observations ($p \leq 0.05$). The negative trend was significant for the wet realization in one case (grassland on soil type 6) for the scenario realizations, and all eight cases showed statistically significant trends for the dry scenario realization.

Influence of factors soil type and land use on soil moisture dynamics

Simulated soil water dynamics were analyzed further by dividing the observation period into two sub-periods, 1955-1980 and 1981-2003, and by calculating differences in soil water content for major land use and soil types in Brandenburg (Fig. 5.7). Average changes in available soil water were small but negative for all soil and land use types in the sub-periods. Trends were significant for 30-45% of hydrotopes for most of the soils, with the highest significance levels for histosols, gleysols and podzoluvisols, which show over 40% significance level. The percentages varied strongly for different land use types: from only 6% for cropland and bare soil hydrotopes to 70% for grassland.

Changes in available soil water content were less distinct in bare soil and cropland, as the soil water content was already low. The decrease of soil water was more pronounced in non-forested wetlands, set-aside and heathland. Forests with a higher percentage of broadleaf trees were characterized by a stronger decrease in soil water than forests with a higher percentage of coniferous trees, whereas their absolute amount of soil water in the past shows hardly any difference. Also

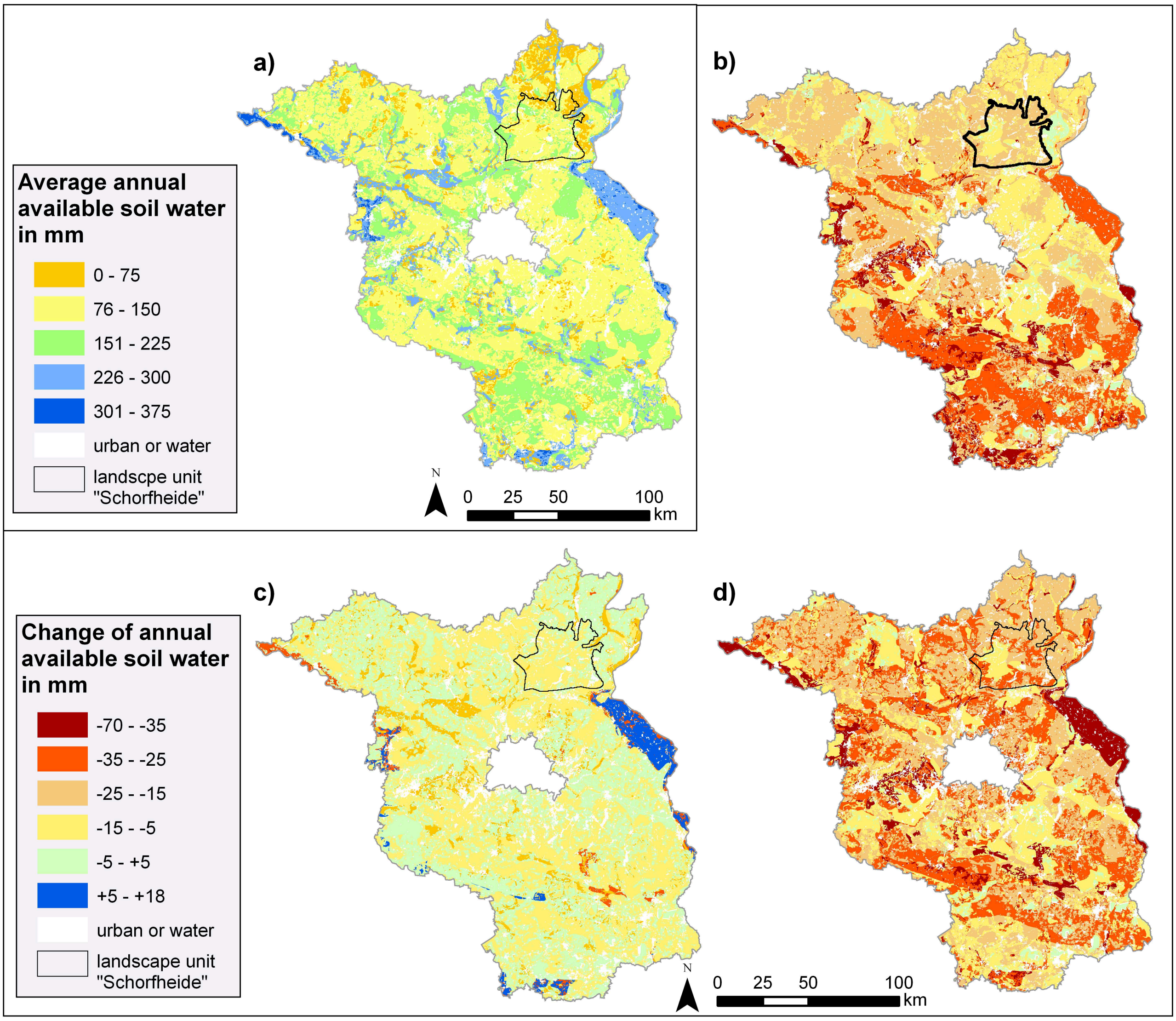

Figure 5.4: (a) Average annual available soil water from 1961 to 1990; (b) changes in average annual available soil water in 2003 compared to 1961-1990; changes in average annual available soil water from 1961-1990 to 2046-2055 for the (c) wet realization and (d) dry realization.

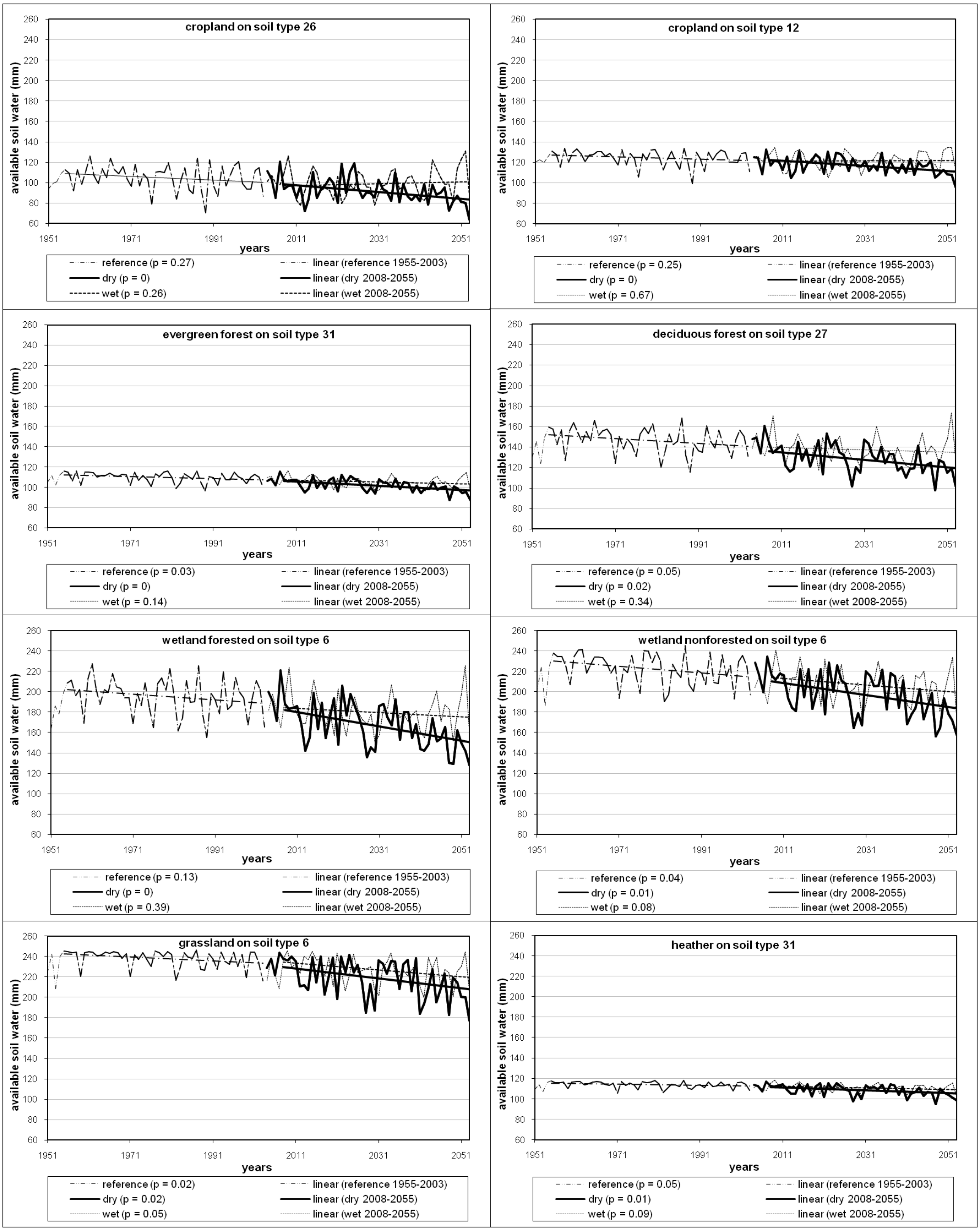

Figure 5.6: Trends of annual available soil water from 1951 to 2055 for the selected hydrotopes for the reference period and the wet and dry scenario realization.

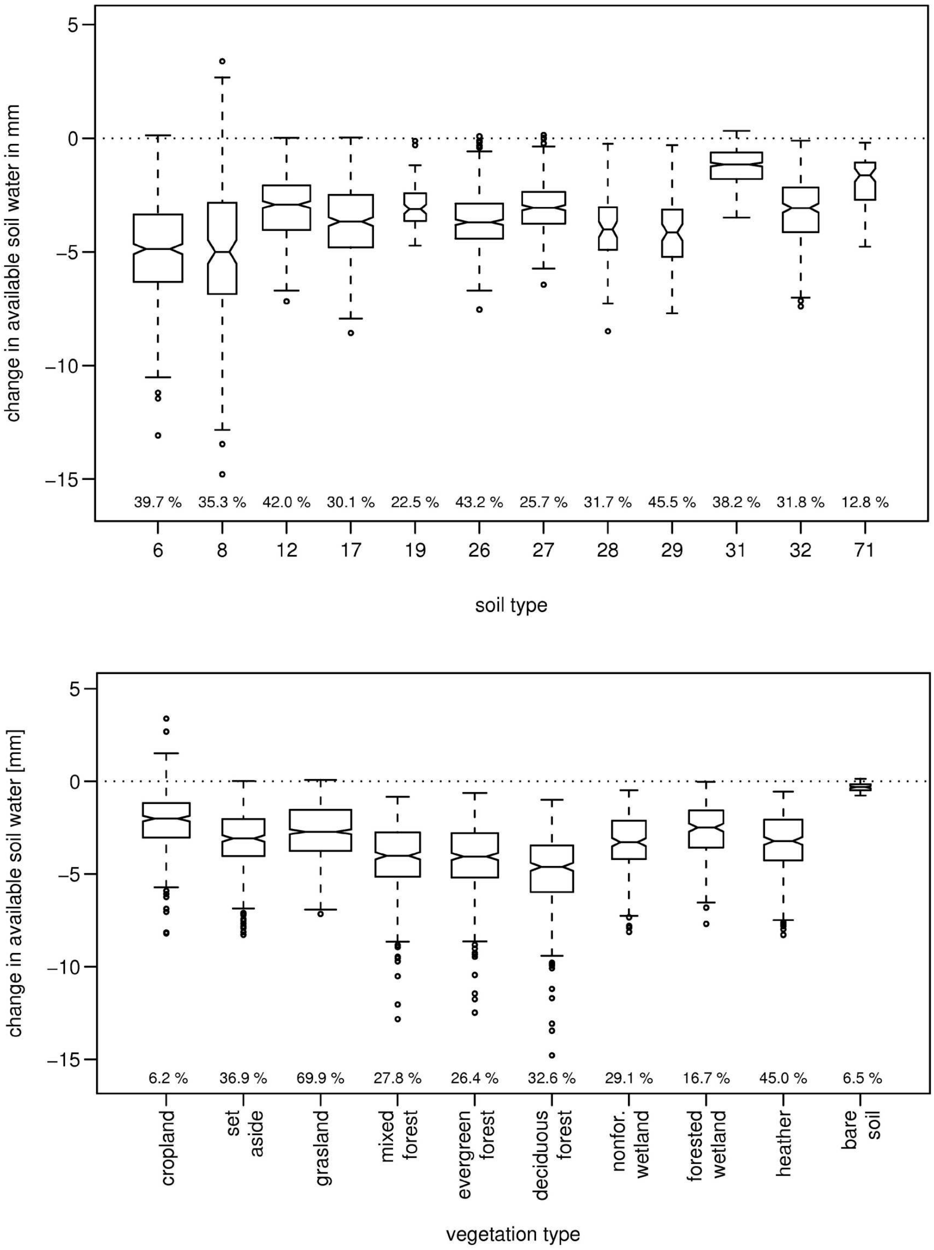

Figure 5.7: Changes of annual available soil water from 1955 to 2003 for (a) soil types and (b) vegetation types in the area of Brandenburg. The width of the bars represent the sample size (63-705 samples), the percent values on the graphs show a share of hydrotopes (by number, not by area) having statistically significant trend for the same time period.

areas with more vegetation cover over the year showed stronger and more significant soil water decreases. Cumulic anthrosols (71) and cambic podzol (31), both soils with a high fraction of sand, were characterized by the smallest decrease in available soil water. Histosols (6) and fluvisols (8), soils with a high silt fraction, showed the highest total decrease in soil water content.

Comparison of trends in soil moisture in Brandenburg and SACs

Average soil water content in the reference period and for three scenario realizations was compared for the whole region and for the SACs within Brandenburg, for annual and summer values, respectively. For all realizations, soil water contents were higher in the protected areas (by about 18-23mm) than for the region as a whole (Fig. 5.8).

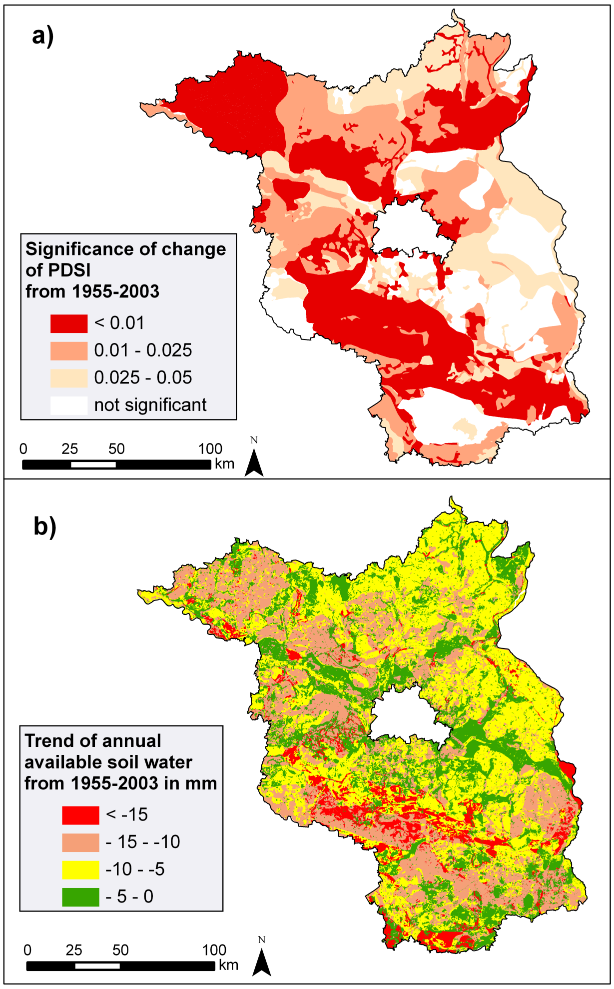

Figure 5.5: (a) Significance of trend in PDSI from 1955 to 2003 for locations of climate stations and hydrotopes, here without vegetation types and (b) trend of annual available soil water from 1955 to 2003.

Average soil water content in the reference period and for three scenario realizations was compared for the whole region and for the SACs within Brandenburg, for annual and summer values, respectively. For all realizations, soil water contents were higher in the protected areas (by about 18-23mm) than for the region as a whole (Fig. 5.8). The order of decline in soil moisture for the three scenario realizations corresponded to expectations for Brandenburg and for the SACs. Average annual available soil water decreased by -6mm (-4%) for the wet realization, by -12mm (-8%) for the medium realization, and by -21mm (-15%) for the dry realization for the period 2046-2055 compared to the period 1961-1990. For the SACs, decreases of -10mm (-6%), -16mm (-10%) and -24mm (-15%) were simulated, respectively.

Simulated soil water content in summer was about 29mm lower than the annual value in the period 1961-1990 (21% for Brandenburg, 18% for SACs). This value increased to a difference of 42-46mm for the period 2046-2055 in the dry realization for Brandenburg and the SACs. Thus, the amount of available soil water showed a stronger absolute decrease for summer values compared to annual values. The standard deviation in Fig. 5.8 indicates larger interannual variation for summer than for annual soil water values. The order of decline in soil moisture for the three scenario realizations corresponded to expectations for Brandenburg and for the SACs. Average annual available soil water decreased by -6mm (-4%) for the wet realization, by -12mm (-8%) for the medium realization, and by -21mm (-15%) for the dry realization for the period 20462055compared to the period 1961-1990. For the SACs, decreases of -10mm (-6%), -16mm (-10%) and -24mm (-15%) were simulated, respectively. Simulated soil water content in summer was about 29mm lower than the annual value in the period 1961-1990 (21% for Brandenburg, 18% for SACs). This value increased to a difference of 42-46mm for the period 2046-2055 in the dry realization for Brandenburg and the SACs. Thus, the amount of available soil water showed a stronger absolute decrease for summer values compared to annual values. The standard deviation in Fig. 5.8 indicates larger interannual variation for summer than for annual soil water values.

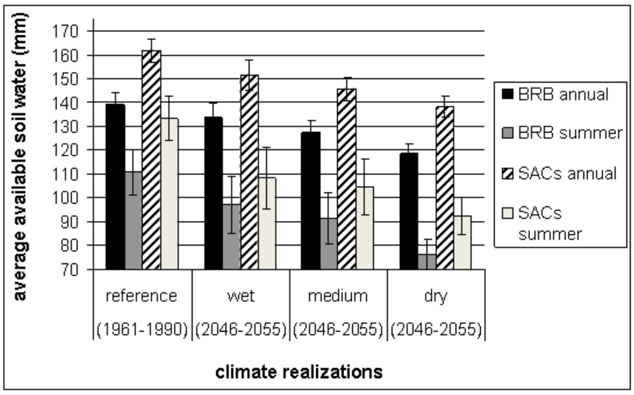

Figure 5.8: Available soil water in Brandenburg (BRB) and the Special Areas of Conservation (SACs) within Brandenburg throughout the year and in summer in the period 1961-1990 and for the three realizations (2046-2055); the standard deviation is shown by the lines.

5.1.4 Discussion

For the first time, changes in soil water were simulated at the very high resolution of hydrotopes by applying the ecohydrological model SWIM (Krysanova et al., 1998). The results indicate that plant-available soil water has decreased in Brandenburg during recent decades, and is projected to decrease even more under climate change. Sound spatial correlation was found in comparing model results obtained for the state of Brandenburg with the Palmer Dry Severity Index (PDSI). The trend in available soil water in Special Areas of Conservation (SACs) within Brandenburg is even more negative than for the whole state with its greater share of agricultural land use and smaller share of wetlands, though the simulated amount of water content is higher.

Methods and modeling

Projections of soil moisture are still very uncertain (Trenberth et al., 2007). The major uncertainties result from the lack of spatially distributed observed soil moisture data for comparison to the simulated values, and inaccuracies in soil parameterization. Nevertheless, comparison of soil water simulated using the model SWIM with observed values for some sites in Brandenburg has given reasonably good results (Post et al., 2007). In this study, calibration and validation of river discharge was carried out using observations for the Havel river basin, representing nearly the entire area of the state for which soil water changes were simulated (Fig. 5.1a). The effects of opencast lignite mining and the irrigation system in the south of Brandenburg on the regional hydrology are large. In the 1980s up to 200 million t lignite per year were produced. In conjunction, 1200106m^3 water per year (Arnold and Kuhlmann, 1993) were pumped out of the mining area into the Brandenburg lowlands. Mining activities were strongly reduced after the German reunification with consequent lowering of river discharge. Yet these activities could not be taken into account in this study. Additional runoff due to water pumping during mining activities accounts for about 11m3 s^{-}1 at Havelberg from 1973 to 1999 compared to 1991-1999 (BfG, 2003).

The model structure is based on distinct hydrotopes. The lateral flows thereof are aggregated to the landscape unit level, and then connected by the river network. The model does not consider lateral movement of soil water between the hydrotopes. For most of the state of Brandenburg with its characteristic lowlands, lateral flows are of little significance for soil water dynamics, yet for some moraine hills there could be a more notable effect. Inclusion of lateral water movement between hydrotopes could amplify the range of soil water changes given a certain soil and land cover type (Naden and Watts, 2001; Jasper et al., 2006), and influence the patterns of change. However, the general results and trends would stay valid. If specific small-scale effects are of interest, another three-dimensional model with connected grid cells should be applied. Further research is needed to include more detailed differentiation of soil and vegetation types concerning soil water processes such as root water uptake.

Changes in available soil water and drought index

SWIM was driven by three climate change realizations, two of which project less annual precipitation than in the past and one projects more (Table 5.2). The trend of available soil water for Brandenburg showed a slight, insignificant decrease for the wet and medium realizations and a strong and significant decrease for the dry realization. Since the realizations were characterized for Germany and not specifically for Brandenburg, the medium realization does not exactly represent intermediate climatic conditions. The simulated decreases in soil water even for the wet realization indicate a strong influence of evapotranspiration (due to higher temperature) on soil water, exceeding the effect of increasing precipitation in the period up to 2055. Other studies simulated a stronger direct influence of precipitation on soil water content under a temperature increase of less than 4K for regions in France and China (Etchevers et al., 2002; Yang et al., 2003). Average simulated available soil water was drastically reduced in the year 2003, which was characterized by exceptionally warm conditions throughout Europe (Fig. 5.4b). Other model studies also report considerable declines in soil moisture for Switzerland and throughout Europe during the summer of this year (Jasper et al., 2006; Fischer et al., 2007). In consequence, a strong reduction of primary productivity of the biosphere in Europe was observed in the same year (Reichstein et al., 2007).

The spatial distribution of soil water indicated that climate parameters generally play a large role (Fig. 5.4). The climate parameters were considered uniform within each landscape unit. Their spatial boundaries are shown in Fig. 5.1. In addition, edaphic conditions influence soil moisture. For example, the most pronounced soil water changes occurred in floodplains of major rivers. Soils in these areas are characterized by higher soil water capacities and could thus be subject to larger potential changes.

The comparison of PDSI changes with trends in simulated available soil water generally showed good agreement between these two independent methods, with SWIM allowing a finer spatial resolution (Fig. 5.5). Results of simulated soil moisture demonstrated the strong influence of both soil and vegetation types (Figs. 5.6 and 5.7). Land use changes and changes in soil characteristics were not considered in this study. Other hydrological models, however, have showed that water flow components react very sensitively towards these changes (Bormann et al., 2007; Yu et al., 2009).

The simulated soil water contents for the different soil types varied according to the field capacity. Hydrotopes with general water limitations like cropland under sandy soils were subject to smaller absolute changes, but larger relative ones. This is in accordance with the results from Jasper et al. (2006), who further point to the associated ecological risk of future soil water changes for soils with currently critical soil water conditions. Soils with a high silt content like histosols or fluvisols were more susceptible to absolute changes than sandy soils. Also, Jasper et al. (2006) indicated higher absolute changes for silt loam than for sandy loam and loam. Naden and Watts (2001) showed a generally minor decrease of soil water for sandy soils compared to clay soils for some sites in the UK under climate change. This can be explained by generally higher levels of soil water in more loamy soils, and by slow capillary transportation of water in sandy soils. Temporal variability was smaller for soils with high sand contents like cambic podzols than for histosols with a high fraction of silt. These results are not in line with expectations (e.g. Mohanty and Skaggs, 2001; Ceballos et al., 2002) and have to be investigated further.

Absolute soil water changes were more pronounced under forest than under cropland and grassland (Fig. 5.7). Jasper et al. (2006) also showed higher relative soil water changes under climate change for forests than for cropland and grassland, but the ranges of absolute changes differed between climate scenarios used. A study using the same model SWIM showed strong reductions in water yield when land use was converted from grassland to forest, due to an increase in leaf area (Yu et al., 2009). The level of significance of soil water change during the period 1955-2003 was low for cropland and bare soil but relatively high for grassland and forests. However, the latter have a high vegetation cover over the year and have been found to reduce their transpiration during warmer periods. Thus, they balance out soil water decrease to a certain extent compared to soils under less vegetation cover exposed to stronger evaporation (Etchevers et al., 2002; Seneviratne et al., 2002; Yang et al., 2003). The absolute reduction of soil water in deciduous forest was higher than in coniferous ones (Fig. 5.7), whereas their absolute amount of soil water in the past shows hardly any difference. This could be due to a prolonged vegetation period for deciduous trees under a warmer climate.

Comparison of simulated soil water with observed values in other studies using the model SWIM suggests some overestimation of root water uptake within the first 70-90cm (Wattenbach et al., 2005; Post et al., 2007). Calibration of this process using measured data could improve the results on soil moisture dynamics and give a better representation of water uptake by plants along the soil profile.

Soils in SACs were projected to maintain higher soil moisture compared to soils for the state as a whole (Fig. 5.8). One likely reason is that histosols or fluvisols with a high water storage capacity are over-represented in SACs (with an areal share of 22% in the SACs compared to 15% in Brandenburg). Thus the absolute future change of soil water in SACs is also larger than for the average soils in Brandenburg. Wetlands must therefore be regarded as vulnerable against climate change.

5.1.5 Conclusion

Simulated available soil water already decreased significantly in Brandenburg, and it is expected to decrease further, independently of the scenarios in question. The spatial pattern is differentiated, as soil moisture is affected by climatic parameters, soil types and land use. Comparing simulated soil water trends with an independent method using the Palmer Drought Severity Index showed a congruent pattern on the overall scale, although the SWIM simulation has a much higher resolution.

Special Areas of Conservation (SACs) show the highest absolute decrease in available soil water. As many wetland areas were projected to be affected by soil water decline, measures to stabilize or increase available soil water are necessary. Yet the results clearly show that SACs stored large amounts of soil water compared to the rest of the state and that these areas will keep this role in future. They are therefore important elements of the hydrological cycle due to their relatively high soil water content. A study for the Nuthe basin, which lies within the Havel river basin, showed that wetlands make a significant contribution to the water balance of the basin due to their high water retention capacity (Hattermann et al., 2006). SACs thus have an important function in regulating soil water conditions in dry areas, as they are able to buffer the impact of climate change to a certain extent.

Furthermore, it was shown that vegetation types have a strong influence on the soil moisture dynamics. The changing pattern of vegetation types in the landscape could therefore represent a possible adaptation measure towards projected changes in hydrological conditions. One possibility is the promotion of permanent crops rather than annual ones, since the former have deeper roots and can access groundwater and better overcome dry spells.

The management practices both within and outside the protected areas should be adapted to the expected decrease in available soil water. In order to achieve the stated conservation goals, it is increasingly important to retain water within the landscape of this relatively dry area. Brandenburg is characterized by many small drainage canals. In consequence of the observed and expected changes in available soil water, these drainage canals should rather be closed where possible, and farmers should be compensated for maintaining the increasingly scarce water within the landscape. Another possibility to reduce runoff and soil moisture decrease is to rehabilitate river systems where possible. The Special Areas of Conservation are essential for local climate and water regulation, and should maintain and improve their prominent function and position as protected areas in Brandenburg.

5.2 Identification of the variable importance for simulated plant available soil water levels

In section 5.1 the soil moisture dynamics in Brandenburg, Germany, were simulated by means of the ecohydrological model SWIM. This dynamical model was applied to evaluate plant available soil water based on observed climatic data from 1951-2003. Soil water calculations are based on the water balance for the soil surface and soil column including precipitation, surface runoff, evapotranspiration, subsurface runoff and percolation processes. The simulation unit are so-called hydrotopes (over 3000 in total in Brandenburg). Each of these is characterized by a set of unique soil, vegetation and climate characteristics. For an overview over the input variables see Table 5.4, their correlation values are provided in Figure A.2. As the porosity, field capacity and saturated hydraulic conductivity are recalculated at the beginning of the simulation, these recalculated values are used here.

To identify the most important input variables to express the simulated available water amount random forest regression tree was applied (Breiman, 2001). the reason for applying a statistical approach is the large computational requirements of the SWIM model for detailed sensitivity analysis. The methods of regression trees has been identified as “powerful tools for analysis of complex ecological data” (De’Ath and Fabricius, 2000). Random Forest is particularly suited for predicting outputs and for assessing the importance of input variables. It considers an ensemble of decision trees, and thus improves model accuracy though a large number of trees. These are are build from the bootstrapped variables, in this case continuous data.

Random Forest regression trees have the advantage that no assumptions on the distribution of data are needed (in contrast to regression models), that they handle large amounts of predictor variables for which interactions are taken into account (which is relevant for complex soil dynamics), has a limited overfitting and that they provide estimates on the importance of predictor variables.

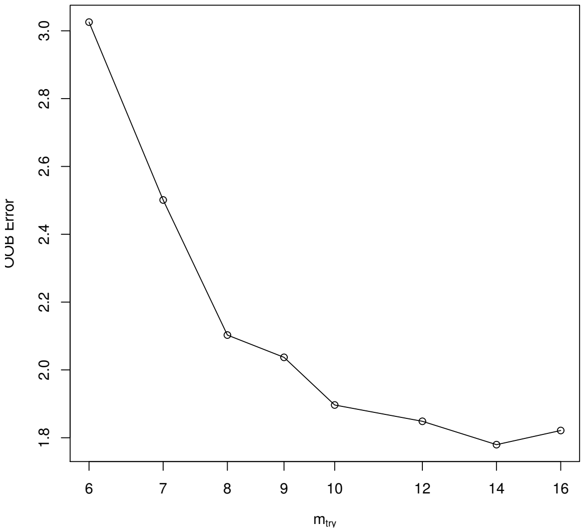

Figure 5.9: Identification of the optimal number of variables selected at each node (mtry) based on the OOB error

A cross-validation of the dataset is already included in the method as each tree is grown with a different randomly selected bootstrap sample and the remaining (”Out of Bag”) is used to test the tree. This is then used for calculating the “Out-of-Bag”-error (OBB). The model has been implemented in R (RDCT, 2009) with the package randomForest (Breiman et al., 2006).

The tree model was first set up to predict the plant available soil water of the upper 100cm of the soil from 1961-1990 as simulated by SWIM for each hydrotope, based on the input variables of the model (the average value of all hydrotopes is 161mm, with ranges from 115mm (1. quartile) to 201mm (3. quartile)). A random number of predicting variables (maximum 23) is selected at each split. The number with the smallest OOB error of the respective model has been selected for the final model (14 variables, see Figure 5.9). The graph of the model error against the number of trees shows a high robustness already below 100 trees. Thus with 500 trees considered for the model, the overall robustness can be considered as good. The overall variance explained by the model is 99.94 and the mean of squared residuals 1.81. The usually stochastically drawn seed was set to 1 to ensure reproducibility of the model.

The importance of the input variables can

Table 5.4: Soil water related input variables of the model SWIM used for the random forest regression tree. For more details on the variables see Krysanova et al. (2000)

Input category	Abbreviation	Name
climate	radiation	global radiation[j/cm^2]
	humidity	relative humidity [%]
	prec	precipitation [mm]
	tmin	minimum daily temperature [°C]
	tmax	maximum daily temperature [°C]
	tmean	mean daily temperature [°C]
soil	clay	clay content (%)
	silt	silt content (%)
	sand	sand content (%)
	SC	saturated hydraulic conductivity (mm/h)
	porosity	porosity (%)
	AWC	available water capacity (%)
	FC	field capacity (%)
vegetation	be	biomass-energy ratio (influences growth rate)
	hi	harvest index (for crops)
	to	optimal temperature for plant growth (°C)
	tb	base temperature for plant growth (°C)
	blai	maximum potential leaf area index
	dlai	fraction of growing season when leaf area declines
	almn	LAI minimum (for forest and natural perennial vegetation)
	sla	specific leaf area (m^2/kg) (for forest and natural perennial vegetation)
	hun	hun heat units
soil and vegetation	CN	curve number (for infiltration)

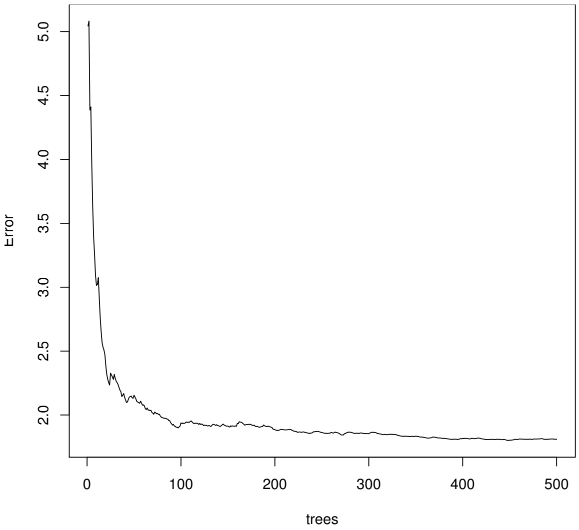

Figure 5.10: OOB model error for 500 decision trees.

be expressed as a first step by the permutation importance: important variables would decrease the model accuracy notably when their values are permuted. Ranking the variables by this criteria, shows a high importance of precipitation, humidity and field capacity (Figure 5.11). Leaving precipitation of out of the model would increase the OOB error by ober 80%.

Climatic and pedological input factors have thus shown the highest relevance in expressing soil moisture levels. However, some variables are strongly correlated, which influences the permutation importance ranking. For example, field capacity is highly correlated (correlation coefficient = 0.94, see Table A.2) with porosity and with soil texture such as the sand (-0.86) or silt content (0.87). The reason for this is that the input variables of soil texture are applied in the model SWIM as a basis for the calculation of these hydrologic parameters. Due to such correlations between variables, a reduction based on the permutation importance criteria is not feasible.

Therefore, as a second step, a sensitivity analysis was carried out by running the above developed tree model with multiply permuted variables (be-

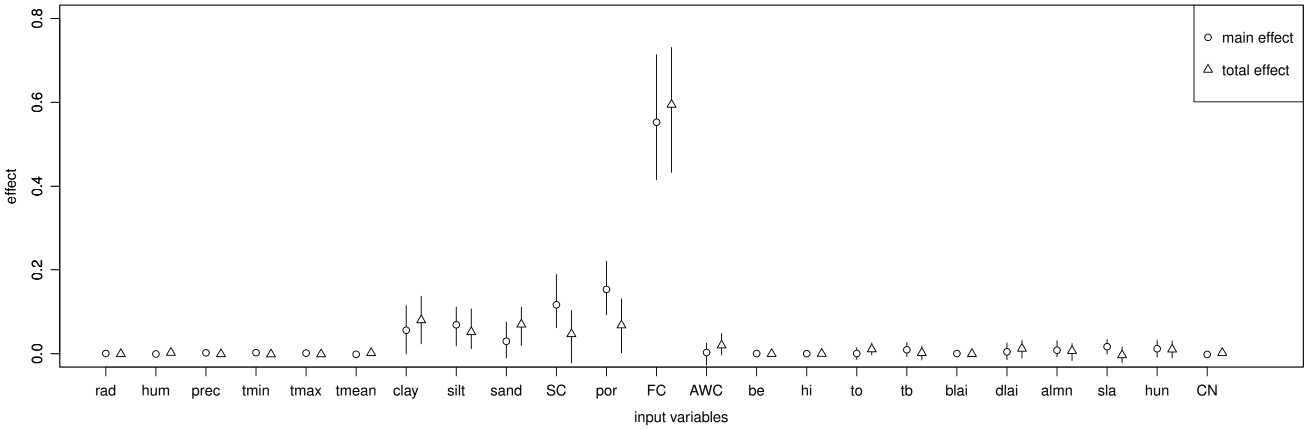

Figure 5.12: Explanation of variance (in %) of the input variables when changing their value between the first and third percentile. The total main effect describes the effect when changing the respective variables while holding others fixed. The total effect expresses the explained variances when also including changes of related variables.

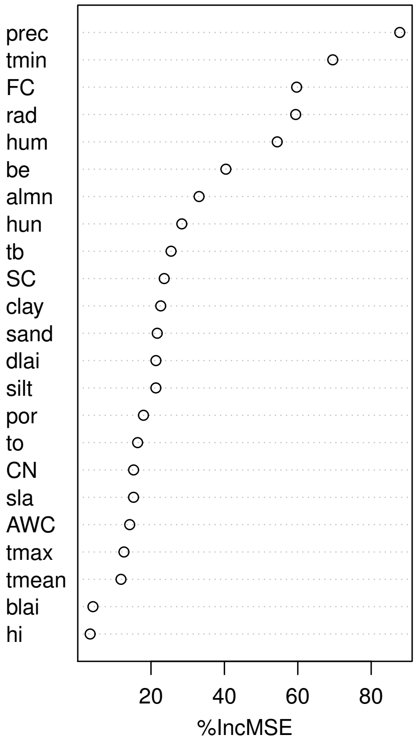

Figure 5.11: Importance of input variables regarding an increase in the mean squared error when permuting their values.

tween the between the first and third percentile) and thus take into account interrelations between input variables (Saltelli et al., 2010; Sobol et al., 2007) (implemented in Pujol et al. (2012)). This has been applied in other sensitivity analysis in order to improve complex hydrological models (e.g. Reusser et al., 2011). The results show a high importance of the field capacity, explaining around 60% of the variance (Figure 5.12). Further pedological factors such as porosity or saturated conductivity play a minor role. This indicates that the long-term levels of soil water could be explained by a smaller set of input variables. But does this also hold for annual changes in soil water, which are more relevant for vegetation as the focus of the study above?

The regression tree model has therefore been set up including annual climatic values for the available years 1951-2003. Due to this large dataset, a random sample of 10% of the data points have been selected as a basis for the 100 trees, with a optimized number of variables at each split of 12. With a mean error of 35.0, the regression tree does not express the simulated soil water contents adequately. The reason could be the buffer capacity of soils, i.e. the dependence on the conditions of the previous years. Therefore, in a next step, the climatic variables of the previous years have been included as input variables (12 variables selected at each split, 100 trees). This reduced the model error slightly to 31.0.

The results indicate that there is a possibility to reduce the complexity of the model for predicting long-term averages of soil water. However, inter-annual changes cannot be well expressed by the developed regression tree model. For this, other also simplified models could be applied instead, which have adequately simulated soil moisture on an intra-annual basis (e.g. Sheikh et al., 2009; Pan, 2003).

6

Discussion and Conclusion

By means of a series of vulnerability and impact assessments for German regions, this thesis aims at advancing the scientific basis of such studies. Although their number has soared due to a demand from policy makers to inform adaptation responses, their scientific foundations remain weak. A new approach of quantifying and aggregating vulnerability components in a multi-sectoral setting has been developed. A more detailed study for the forestry sector strengthened the concept to enable absolute statements on the severity of impacts for different regions on the basis of empirical damage data. However, these assessments are still fraught with high requirements regarding the applied methods and data and involve multiple components. Therefore, in subsequent analysis the potential of reducing their complexity was explored, while at the same time ensuring a sound scientific basis.

6.1 Discussion of the research questions

The main findings of the previous chapters are now summarized and discussed in more detail, structured along the posed research questions. Each section begins with a short summary of the identified challenge, which is then addressed based on the work of this thesis. Finally, a brief answer to the research questions is given in a text box.

6.1.1 How to quantify components of vulnerability? (RQ1)

Identified challenge: The quantification of vulnerability components requires a notion of the vulnerable entity, the stimulus and the direction of the change. Previous multi-sectoral studies have shown inconsistencies in implementing this. To then quantify the components on a sectoral level, appropriate methods are partly lacking.

To conduct a multi-sectoral vulnerability assessment for municipalities in North Rhine-Westphalia (Chapter 2), sector-specific indicators representing the vulnerability components were developed. A quantification was achieved for a wide range of sectors, including the social and biophysical dimension, which is an advancement to studies commonly focusing on one of these dimensions (Füssel, 2007). For the calculation of most indicators of exposure and sensitivity, existing methods could be applied (e.g. quantification of soil erosion based on the Universal Soil Loss Equation (Schwertmann et al., 1990; Renard et al., 1997)), for others, new approaches had to be developed. This was the case for the quantification of sensitivity of humans to heat waves by means of a fuzzy-logic based model (Lissner et al., 2011) (see also the list of publications related to this thesis), the identification of a relevant climate-related proxy for forest fires (Holsten et al., 2013) (Chapter 4) and the quantification of sensitivity of forests to windthrow based on observed storm damage data (Klaus et al., 2011) (Chapter 3).

For this quantification, in general, two lines can be followed: a deductive or inductive based approach:

Quantification via a deductive approach: For the multi-sectoral North Rhine-Westphalia study (Chapter 2), first, the potential impacts to consider were identified. This was based on the regional relevance of the sector and impact processes and their climatic dependence, according to scientific findings from the literature. However, due to a lack of data, this selection was restricted. Thus, some highly relevant and climate dependent sectors for the state could not be considered given the data scarcity, e.g. water use of the energy sector for cooling purposes.

In total, ten impacts could be included in the analysis. For each of these (e.g. flash floods) a clear sensitive entity was defined (e.g. settlements) and related to a direction of change for a specific climatic stimuli (e.g. increase in impact due to increase in days with heavy precipitation). Following this structure, the system boundaries could be clarified and the sensitivity of the respective entity directly related to the specific climatic stimuli.

In detail, the quantification of each vulnerability components was based on a rescaling procedure based on the minimum and maximum value within the study area. The exposure was quantified by changes in climatic stimuli until the end of this century, relative to the data set of all municipalities. To account for both directions of change, the absolute maximum value of either direction was taken as the maximum rescaled value (-1 to 1). The climate data was obtained from simulations of two regional dynamical climate models, which differ, especially in their output of hydrological variables and therefore provide a range of possible consequences.

The quantification of the sensitivity component unsing indicators was especially challenging, as it required tailored methods for each sector. As a dimensionless characteristic of the system, this component was then rescaled for each sector between 0 and 1. This differs from Yoo et al. (2011) who consider also negative values of sensitivity, leading to beneficial climatic impacts (e.g. the commercial sector could benefit from warming). In this thesis, this is already represented by the different directions in climatic stimuli.

The third component of vulnerability, the adaptive capacity, is often neglected in literature on vulnerability to climate change (Engle, 2011). In this thesis it has been integrated in a generic manner as a cross-sectoral capacity (following Metzger and Schröter, 2006; Yoo et al., 2011). A focus was set on private and public economic resources and the knowledge and awareness of citizens. Not only the educational level was taken into account here, but also regional climate change and sustainability related initiatives in a novel way. This way, the personal motivation and actions at a local scale of municipalities is expressed, which play a key role regarding the adaptation to climate change (Measham et al., 2011).

A similar procedure of rescaling has been applied in assessments on bushfires (Preston et al., 2008) or rural communities in Australia (Nelson et al., 2010a). However, in these studies, the rescaling was based on percentiles of the data set, which led to a change in the distribution of the values. Consequently, the differences in values between regions would be changed. This information on the level of difference between the municipalities is still available when applying the presented approach of this thesis.

The proposed approach achieved a direct relation between relevant climatic stimuli and sensitive entities as well as a comprehensive quantification of all vulnerability components. It followed a deductive argumentation based on literature, which allowed the establishment of a link between exposed entities and climatic stimuli based on existing information in a deductive manner. A major limitation is the paucity of empirically based impact thresholds (for example above which an exposure or sensitivity indicator would cause significant impacts). Thus, only a relative quantification based on the minimal and maximal values of the data set was possible. This means that the study is restricted to a comparison within the study region. In other words, absolute statements about whether a municipality is actually vulnerable are hindered. A solution to this shortcoming has therefore been developed, based on an example of the forestry sector for the region.

Quantification via an inductive approach:
A quantification with absolute levels via an inductive approach has been achieved for windthrow impacts for the same state of North Rhine-Westphalia (Chapter 3). Here, empirically grounded sector-specific thresholds of climate impacts could be identified. For this, information

on forest areas affected by windthrow damages from the storm event “Kyrill” could be applied, which caused severe damage throughout the state in the year 2007. The sensitivity was expressed by the probability of damage for such high wind speeds. For example, a sensitivity value of 0.1 indicates a windthrow for every tenth storm of similar strength to that of the observed event. It was based on a regression model, which describes the observed spatial pattern of damage with respect to biophysical and topographic characteristics of forests stands.

The identification of exposure thresholds was based on observed extreme wind speeds at climate stations during this event. This component was therefore expressed by storm damage probability which is the reciprocal of storm damage recurrence rate. Consequently, the climate impacts are then represented by the the storm damage recurrence interval.

This sectoral study thus exemplarily showed how damage thresholds, indicating the thresholds for relevant impacts, can be quantified. Given similar empirical damage information for other sectors, these absolute thresholds could also be applied to other sectors within the proposed approach and hence strengthen the outcomes of vulnerability assessments.

Some vulnerability components could be quantified either by existing approaches; for others new methods had to be developed. A systematic structure for combining regionally relevant and sensitive entities with the corresponding climate stimuli is crucial. By developing such a structure and applying it to a study region, a quantification over a wide range of sectors was achieved. A major limitation, however, still lies in the empirical foundation of the quantification.

6.1.2 How to combine components of vulnerability and sectoral impacts? (RQ2)

Identified challenge: While the applied definition of vulnerability can be seen as a function of the components exposure, sensitivity and adaptive capacity, it lacks an indication of their aggregation.

Aggregation procedures can be employed when combining vulnerability components. Chapter 2 presented a way to combine exposure and sensitivity in a transparent manner by proposing that both the absence of climatic changes (zero exposure) and an insensitivity (zero sensitivity) to these changes are reflected by zero impacts. This can be achieved by a multiplication of the two components, leading to impacts ranging from beneficial to disadvantageous consequences of climate change. A different approach was followed by Rannow et al. (2010) and Preston et al. (2008) who average exposure and sensitivity values. This, however, leads to a substitution of the two components. Consequently zero climatic changes could be compensated by a high sensitivity, leading for example to a medium impact.

To finally aggregate the impacts and adaptive capacity, a visual approach of combination was applied based on Metzger and Schröter (2006): for each municipality impacts are expressed by the hue, the adaptive capacity by different levels of transparency. This then led to a two dimensional color code. Instead of taking a generic approach, the adaptive capacity could also be quantified in a sector-specific way and directly related to the respective impact (see for example Luers et al. (2003) for agriculture or Perch-Nielsen (2010) for tourism). However, this was not feasible for the study region due to a lack of data for the wide range of included sectors.

Besides combining vulnerability components, aggregation procedures can be applied for a cross-sectoral overview in a multi-sectoral assessment. For comparing the suitability of methods to aggregate across sectors, the arithmetic mean of sector-specific impact values and a typological categorization have been applied to the multi-sectoral vulnerability analysis in Chapter 2.

Cross-sectoral aggregation via an arithmetic mean:

Prior to calculating the arithmetic mean over the sectoral values, the sectors were grouped into the physical, social, environmental and economic dimension. The sectors or dimensions could then

Table 6.1: Advantages and disadvantages of the presented two aggregation approaches across sectors based on the arithmetic mean and the typological categorization of sector-specific impact values, presented in Chapter 2

Approach	Advantages	Disadvantages
Arithmetic mean aggregation	Quantification of aggregated impact burden across sectors Transparent formalization of procedure Decisive factors can be traced back to sector-specific impacts, sensitivities or exposures	Subjectivity due to weighting factors between impacts or sectors Approach allows for a compensation of positive and negative impacts across sectors
Typological aggregation	Impacts between sectors are not compensated Regional typologies are identified Individual impact values can be inferred from the clusters Decisive factors can be traced back to sector-specific impacts, sensitivities or exposures	Total impact burden not quantified Subjectivity due to weighting factors between impacts or sectors Formalization of procedure less transparent Coarse resolution of results

be assigned a weighting factor. Due to a lack of regional information from the stakeholder perspective on the weighting factors of these sectors and dimension, equal weights were assumed here. Additionally, unequal weights, based on a stakeholders survey on the European level (Greiving et al., 2011a) were also tested, but showed only a small influence on the results. This aggregation procedure provided an impact burden across sectors. Due to the built knowledge base on the sector-specific impacts, the vulnerability creating factors can still be traced back to the decisive factors. However, it also involves subjectivity due to different weighting factors for the sectors or dimensions. Also, the cross-sectoral aggregation by an arithmetic mean allows for compensation between sectors. Thus negative consequences in one sector could be compensated by positive ones in a different sector. This could lead to an overall minimal impact, although consequences of climate change are apparent for the single sectors.

Cross-sectoral aggregation via an typological approach:
As an alternative method, a typological categorization via a cluster analysis has been further applied to aggregate the same sector-specific impacts. This yielded a typology of municipalities which are faced with a similar impact burden. For the case of North Rhine-Westphalia, three “impact regions” were identified, the Rhine Valley dominated in terms of consequences due to heat waves, the Westphalian Bay had more balanced impacts over the sectors and the mountainous regions had high impacts on the forestry sector such as windthrow. Also this approach involved some subjectivity due to the weighting factors of the sector-specific impacts used in the cluster analysis, which were here equally weighted. A total impact burden was not provided, however, this way a compensation of negative and positive impacts across sectors was avoided. A main advantage of this approach is that it identifies regional “impact-profiles”, summarizing the regional situation. It also allows us to trace the decisive factors of the clusters back to the sectoral perspective. However due to the complex method of a cluster analysis, this process is not as transparent as calculating the arithmetic mean. Furthermore, the aggregation leads to spatially coarser impact results. This study is an advancement to a cluster analysis carried out for the same region by Kropp et al. (2006), which included only a limited set of sectors expressed by indicators of sensitivity instead of vulnerability (according to the terminology of vulnerability followed in this thesis).

To sum up, these two presented methods for an aggregation of impacts across sectors (via an arithmetic mean of sector-specific values or a cluster analysis) represent alternative methods which are suitable to give an overview over the total impacts of a region. However, they both entail advantages and disadvantages which, have to be carefully considered in the light of the aim prior to carrying out a vulnerability assessment (for an overview of these discussed characteristics see also Table 6.1).

For the aggregation of vulnerability components, regions of zero impact should exhibit either insensitivity towards relevant climatic stimuli or no future climatic changes, which can be achieved by multiplication. Regarding the cross-sectoral aggregation, two possible approaches have been presented. However, both have a set of advantages and disadvantages. Their application should be considered in the context of an assessment.

6.1.3 How much complexity is needed? (RQ3)

Identified challenge: Conducting vulnerability assessment requires extensive resources. A challenge lies in reducing the level of complexity without losing informative power.

The previous discussion on the application of vulnerability assessments has revealed that the quantification and integration of all components is a challenging task. A common aim of vulnerability assessments is to support the decision making regarding adaptation efforts (e.g. Schröter et al., 2005b; Füssel and Klein, 2006). But what level of complexity of the vulnerability concept is really required to support adaptation responses? This question has first been addressed by the sectoral case study on forest fires in German federal states (Chapter 4).

The temporal pattern of forest fires is an important indication, which informs the allocation of resources for fire fighting. In Germany, for example, more than €2 million were spent on forest fire prevention in the year 2011 (BLE, 2012). The periods of high fire risk are especially important, which are currently taking place end of April to May and in the late summer. A change in this pattern would require an adjustment of the regional fire risk management. In order to develop projections of future temporal dynamics and improve prevention measures, it is necessary to identify a suitable proxy for the occurrence of forest fires. Therefore, five different indices of forest fire danger and four meteorological variables were systematically analyzed regarding their performance as a proxy for forest fire occurrence in Germany (monthly number of fires). These ranged from single meteorological variables (such as temperature, precipitation or relative humidity) to complex fire danger indices, such as the Canadian Fire Weather Index, which includes various modules representing fire processes (see Figure 6.1). Each of these indices is widely used over different regions for predicting the meteorologic forest fire risk. However, systematic assessments of such indices, as carried out for example for Spain (Padilla and Vega-García, 2011) or Austria (Arpaci et al., 2013) are rare and were lacking for Germany.

In this study it was shown, that the monthly pattern of the number of forest fire in each state can be well represented by meteorological indices and particularly by the relative humidity value. For the most fire prone state in Germany, Brandenburg, the correlation coefficient between the monthly number of fires and relative humidity (using the Spearman's rank correlation test) even amounted to the high value of 0.9. This highlights, that meteorological factors alone are here already a well suited proxy to describe the temporal pattern, even without the consideration of vegetational or anthropogenic influences. Regarding the vulnerability framework applied in this thesis, this means that the exposure component alone is well suited to express the impact component, in this case the occurrence of forest fires. For other states however, e.g. Rhineland-Palatinate, the modified M-68 index was a better suited proxy. Because this included also vegetational characteristics, which can be categorized under the sensitivity, this vulnerability component might play a larger role here than for other states.

The results of this forest fire analysis were also interesting due to the fact that the single variable relative humidity outperformed more complex indicators for most of the states. This is even more intriguing considering that this meteorological variable itself is fed into most of the considered fire danger indices, including the modified M-68 index used by the German Weather Service to inform about daily fire risk (Friesland and Löpmeier, 2007). Besides

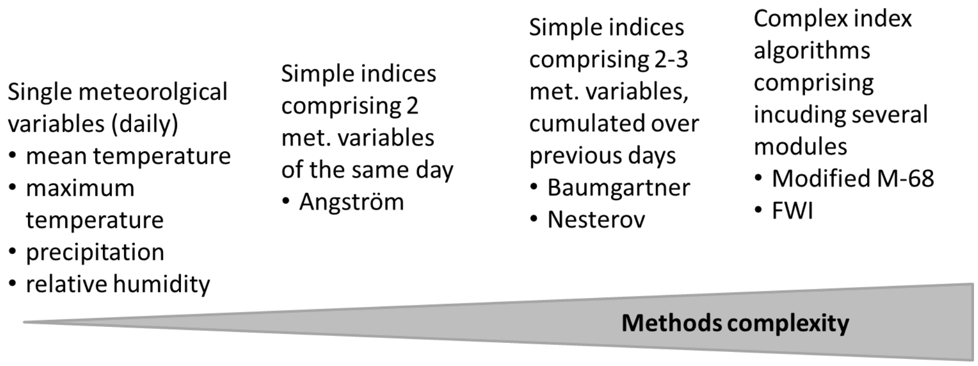

Figure 6.1: Range of complexity of proxies for the impact forest fire occurrence analysed for German federal states in chapter 4.

using the Spearman's rank correlation test, the strong performance of relative humidity was additionally strengthened by means of further statistical methods such as a percentile-rank and an ROC curve analysis. This was also the case regarding daily forest fire occurrence for Brandenburg. The results support the practical application of relative humidity as a proxy for forest fire occurrence compared to commonly used fire danger indices, which can be directly measured in the field. Although it is only a single climate variable, its good performance as a proxy is plausible since it already integrates information on temperature, precipitation and the biophysical processes of the surroundings. The good performance of a single meteorological variables agrees well with recent studies from Spain (Padilla and Vega-García, 2011) (temperature and relative humidity) and Austria (Arpaci et al., 2013) (temperature). These new insights can support the adaptation to forest fires by improving warning systems.

A second possible method for the quantification of vulnerability components are dynamical modeling approaches. This thesis therefore further applied the ecohydrological model SWIM (Krysanova et al., 1998) to evaluate the impacts of climate change, exemplary for the soil moisture dynamics for the state of Brandenburg, located in the driest part of Germany. It included hydrological processes such as infiltration, runoff, evapotranspiration, plant growth and states of plant stress. These were based on fine-scaled spatial data, such as soil and vegetation characteristics, topography and climate, which characterize the hydrotopes as the core unit of analysis. Thus, the applied modeling procedure generally requires an extensive set of inputs and involves considerable time resources. Therefore, the potential to reduce the complexity of the model was further analyzed. This could be reflected in the dominance of specific input factors on the analysed output of plant available soil water. For example, the temporal dynamics of soil moisture displayed for selected hydrotopes (Figure 5.6) with different combinations of vegetation and soil types suggest a strong influence of soil properties on average available soil water levels. A Random Forest Regression Tree was therefore applied to the dataset. This is especially suited for large datasets, as is the case here. The inter-annual variations could only be represented poorly by the Random Forest Model. To improve the representation, other simplified soil water models could be applied, which have adequately simulated soil moisture on an intra-annual basis (e.g. Sheikh et al., 2009; Pan, 2003). On a long-term time horizon of three decades, the results show a good performance of the built Random Forest Model. In this case, the soil characteristics, in particular the field capacity, dominate regarding the explantation of the simulated soil moisture values. This indicates that there is a possibility to reduce the complexity of the model by a reduction in input variables for predicting long-term averages of soil water. However, the results are limited, especially by a lack of empirical information of soil water contents for validation.

There is a potential to reduce the complexity of vulnerability assessments. As an information basis for developing adaptation measures, depending on the system of consideration, the consideration of one of the vulnerability components could suffice. Even for commonly used methods to quantify these vulnerability components, such as the exposure to forest fires, a simplification is feasible without losing informative power.

6.2 Lessons Learnt

The series of assessments of vulnerability and its components has shown that such studies are still a complex scientific undertaking. Following the terminology as commonly used in the climate change community, many problems arise when implementing this theoretical framework for regional studies. Advances in overcoming the shortcomings of previous studies have been made in this thesis by constructing a new systematic structure of characterizing and aggregating the vulnerability components, with a subsequent application to a case study.

Today, a wide range of methods is available to quantify sensitivities or impacts for specific sectors, from simple indicators to complex modeling approaches. However, to achieve a multi-sectoral assessment for municipalities like in North Rhine-Westphalia, for many climate related and regionally relevant sectors, suitable methods were still lacking. This gap could be filled by detailed sectoral studies, for example for the forestry and health sector, for which new methods have been developed. Nevertheless, the multi-sectoral study was restricted by a lack of data for highly relevant sectors such as energy production.

The work has shown, that multiple approaches of operationalizing the theoretical vulnerability framework exist regarding the quantification and aggregation of sectors and vulnerability components (confirming the first hypothesis). However, they all entail specific advantages and disadvantages which have to be carefully considered before application.

The case studies have further revealed that there is a potential to reduce the complexity of some approaches (confirming partly the second hypothesis). For example the superiority in performance of commonly used complex indicators over simple climatic variables as a proxy for forest fire occurrence, had seldom been questioned before. Yet, this thesis could only shed light on specific aspects of complexity for two impacts. More systematic comparisons and assessments of the complexity and performance of existing methods to quantify vulnerability components are therefore needed.

6.3 Conclusions and outlook

Still no universal “toolbox” or conceptionalization is available for decision-makers to engage in such assessments themselves. It is questionable whether this is feasible in future. Rather, this thesis has shown that the selection of sectors to include or methods to apply depends on the regional context and the aim of the study. A critical scientific-based discussion on the applied concept and framework therefore remains essential. In other words, the application of a vulnerability assessment requires an understanding of the context of the study and the methodological constraints.

More systemic approaches and discussions on suitable methods are needed. Especially the current “indicator fatigue” in vulnerability assessments (Malone and Engle, 2011) could be alleviated by a more systematic and scientifically sound approach for their application. Moreover, by enhancing the understanding of vulnerability processes, the number of studies directly supporting decision-makers could then be increased, which are currently only representing 9% of existing assessments (Preston et al., 2011).

This thesis has made a first step towards a reduction in the complexity of vulnerability assessments, regarding the considered components as well as the applied quantification methods. But more research is needed on evaluating and comparing the performance of existing methods.

Making the vulnerability concept operational in case studies, according to the definition as used in the climate change community, is still a challenging task. Currently this definition is undergoing an evolution. This is apparent from a recent Special Report on extreme events and disasters by the IPCC (IPCC, 2012), which defines vulnerability in an even wider sense as "the propensity or predisposition to be adversely affected". However, this concept will also entail further extensive discussions on specifying these terms further in the context of climate change. More studies will subsequently follow on making assessments based on this definition operational.

While climate change is continuing to take place, adaptation will - in addition to mitigation - play an important role. At the UN climate change conference in Doha, in December 2012, a new aspect has been considered in the negotiation process: the compensation of damages. Thus, the Conference of the Parties "agrees that comprehensive, inclusive and strategic responses are needed to address loss and damage associated with the adverse effects of climate change" and invites "assessing the risk of loss and damage associated with the adverse effects of climate change, including slow onset impacts" (**?**). Although implying a forward-looking notion of vulnerability, climate change vulnerability and impact assessments could be a helpful tool to evaluate damage for compensation measures related to climate change. However, to achieve absolute such quantifications on impacts or vulnerabilities, more empirical based studies, such as presented for windthrow in forests, are necessary.

7

Appendix

Appendix A: Supplementary Material to Section 2.1

Methods of sensitivity indicators

In the following, sensitivity indicators applied in the vulnerability analysis are described in detail:

Urban areas at risk of flash floods can be quantified by a combination of flow accumulation analysis with land use data (Castro et al., 2008). We calculate the potential runoff by applying the Curve Number method (USDA, 1972, 2007), which accounts for land use (based on the ATKIS25 dataset)and hydrological soil types with the ArcCN tool developed by Zhan and Huang (2004) implemented into ArcGIS. We assigned Hydrological Soil Types (A = high infiltration capacity and low runoff to D=low/high respectively) to soil types of the regional soil map for NRW (BK50) by applying the criteria concerning minimum hydraulic conductivity, depth of least permeable layers and depth to water table (USDA, 2007). Flow accumulation is then analyzed with ArcGIS based on the potential runoff and the flow direction of the elevation model (DEM50). Considering the potential time lag of the flow (assuming a hypothetical 60 min event with 10 mm precipitation and taking into account the slope and runoff potential), the peak flow is quantified based on Castro et al. (2008). We then calculate the share of urban area (ATKIS25 data) affected by a high peak flow of $> 1m^3$ on the total municipal area.

To analyze to sensitivity to pluvial flooding we combine the approaches of accumulated surface runoff and landscape sinks. Using ArcGIS, we identify sinks within the relief and calculate the amount of runoff necessary to completely fill each sink, dependent on the sink volume, drainage area and the surrounding topology. Values for the potential runoff are calculated according to the above described methodology of flash floods. The volume of the sink, which would be potentially flooded, is then divided by the calculated runoff of the respective drainage area. Only settlement area (ATKIS25 data) within these sinks was considered. The value concerning the ratio between drainage area runoff and sink volume was summed for the municipalities and weighted by their area.

The sensitivity of humans to heat is applied from Lissner et al. (2011). This indicator comprises the sensitivity of the population, expressed by the share population $\geq$65 years or older (in 2007). The potential for an urban heat island (UHI) is represented by the degree of urbanity, expressed by the minimum value of either the population density and the share of sealed surface. A fuzzy logic algorithm is applied to the identified influence variables. Thresholds for population density were defined at 250 persons/m^2 and 100 persons/m^2, for the area of sealed surface at 12.5 % and 40 % and for the share of elderly population at 19 % and 29 %. Sensitivity below the lower thresholds is assumed to be very low, above the higher thresholds to be very high; in between a linear increase in sensitivity is assumed. The fuzzified variables sealed surface and population density were aggregated to indicate an UHI effect and then combined with the share of elderly population.

The sensitivity of protected areas describes the susceptibility of its terrestrial habitat types towards drier and warmer conditions. It comprises information regarding biogeographic conditions, based on sensitivity values of Petermann et al. (2007) regarding the restriction of current area borders, ground water dependency, trend in area decrease in the past, restriction to high altitudes and neobiota influence for habitat types in Germany. We substituted their further proposed indicator "qualitative risk" by the locally available indicator "conservation state" from the Natura 2000 database, to indicate already existing pressures imposed on the habitats. We further extended this data by information on cold and wet-tolerant characteristic plants of the habitats, which are expected to be especially sensitive to warmer and drier conditions (Petermann et al., 2007; Araújo et al., 2011). These were defined by their temperature-tolerance (values 2-4) and moisture-tolerance values (values 7-9) based on Ellenberg (1992) and FloraWeb (BfN, 2011). Indicator values were assigned by equidistant categories of the share of these plants on the characteristic plant pool, from 0-100 %. From the same dataset of characteristic plants, the share of stenocious species regarding temperature and moisture conditions (not indifferent to these conditions) was calculated and classified analogously. The average of the 10-subindicators was calculated for each habitat type. The sensitivity of the SAC is calculated according to the area covered by its habitats for 454 out 518 SACs based on available data. The indicator is then multiplied by the share of protected areas within the municipality.

Shallow lakes are especially sensitive to a decrease in water volume (Scheffer and van Nes, 2007). To therefore indicate the sensitivity of lakes to this exposure, we calculated the ratio of lake surface area [m] to lake volume [m](two commonly available indicators). Municipalities, which do not comprise lakes or with a lack of data were assigned the lowest sensitivity. Anthropogenic interventions (i.e. water withdrawal, land use changes or agricultural activities) can also affect the water balance and water quality of lakes (Bates et al., 2008). However, these influences are difficult to quantify. Thus, we focused on natural lakes and lakes evolved through excavation, which are common especially in the Rhine valley due to gravel mining. Thus, a total of 8 natural and 91 excavation lakes are considered. The indicator is then multiplied by the share of lake area within the municipality.

Soil erosion can be estimated by the Universal Soil Loss Equation (Schwertmann et al., 1990; Renard et al., 1997) comprising sensitivity variables of soil erodibility, slope, slope length, cultivation and soil conservation. Slope length cannot be sufficiently calculated based on the available elevation data of 50m resolution. Also, the inclusion of anthropogenic factors like cultivation and soil conservation measures is restricted due to lack of data. Thus, we apply this formula in a simplified way by considering the erodibility (K-factor, derived from the soil map BK50) and slope (S-factor, derived from the DEM50). We therefore describe the potential and not the actual soil erosion sensitivity, which can be further influenced by agricultural activities. The variables are converted to a scale of 0-1 and multiplied according to the equation. Only agricultural soils are considered, since soil erosion is most relevant for these temporarily uncovered and anthropogenically influenced sites. The indicator is then multiplied by the share of agricultural area within the municipality.

The sensitivity of forests to windthrow is applied from Klaus et al. (2011). It comprises forest characteristics (forest composition and state of anthropogenic influence, distance to forest edge), soil characteristics (suitability for decentralized seepage, porosity, cation exchange capacity, depth to groundwater table, soil moisture level, soil erodibility, soil quality, grain size) and topography (slope, altitude, curvature, aspect, hillshade with regard to westerly directions). These variables have been aggregated by Klaus et al. (2011) by means of a logistic regression model validated for the storm event "Kyrill", which caused severe forest damage in the year 2007 in NRW (MUNLV, 2010). We finally multiplied this indicator by the share of forests within the municipalities.

A multitude of factors concerning climatic, environmental and human determinants play a role for the occurrence of forest fires (Cardille et al., 2001; Syphard et al., 2008; Costa et al., 2010; Reineking et al., 2010). A key factor is the fuel moisture, which is influenced by soil moisture conditions (Nelson, 2001; Bartsch et al., 2009). Since spatially explicit data on fuel biomass for forest in NRW is lacking we apply soil moisture characteristics (potential available field capacity of the soils) under forests. Considering the observed forest fires in NRW from 1993-2009, burnt area was 1.55 times higher for needle leaved forest than for broad leaved. This ratio is taken into account for the sensitivity, by assigning needle leaved forest the highest value (forest area from ATKIS dataset). Besides vegetational and pedologic factors also humans influence forest fires, especially through the accessibility of forests (Chuvieco et al., 2010; Costa et al., 2010; Reineking et al., 2010). We implement this by the distance of the forest to the nearest settlements (settlements based on on CORINE). This dataset was preferred over the regional ATKIS dataset to account for distances to objects outside of the state. All three indicators are normalized and averaged with equal weight and multiplied by the share of forests within the municipalities.

The sensitivity of winter tourism to climate change is considered to be especially high for resorts in low mountain ranges (Sauter et al., 2009; Steiger, 2010). In NRW all ski resorts are located in such area of comparatively low altitude, the Sauerland and Eifel mountains. Thus the size of the skiing area is regarded as a proxy for the sensitivity here, expressed by the length of ski runs within the municipality. Due to more advantageous conditions, ski resorts within the core area identified by Roth et al. (2001) are considered to be half as sensitive as areas in the surroundings. Regarding the Eifel mountains, for Monschau only the number of lifts was available, thus the length of its ski runs was set to the average length for the remaining resorts.

The soil moisture regime is considered as one of the main determinants of constraining plant growth (Müller et al., 2010). In Germany, soils most affected by yield decreases under climate change are characterized by low water retention capacities (Wechsung et al., 2008). We therefore express the sensitivity of agricultural soil in NRW to drought by the potential available field capacity under agricultural land (based on ATKIS data).The indicator is then multiplied by the share of agricultural area within the municipality.

Methods of adaptive capacity indicators

The quantification of the generic adaptive capacity focuses on economic resources and knowledge and awareness. The former is described by the personal (household level) as well as municipal financial situation. Regarding the private households, we consider their available income in 2009 according to the State office for Information and Technology NRW. Regarding the public finances, most municipalities had a balanced budget in 2009, however 17 are currently or in the upcoming years overindebted and are thus under the supervision of public authorities. We classified the status of financial budget of municipality as follows, the number in brackets indicate the number of municipalities falling into the respective category: 1= truly balanced (39), 0.8= virtually balanced (281), 0.6= approved reduction in common reserves without obligation of budget consolidation concept (38), 0.4= approved budget consolidation concept (13), 0.2 = budget consolidation concept not approved (50), 0 = overindebted (17). For six municipalities, the decision on the budget consolidation concept were still open at the end of 2009, thus we chose the classification of a non-approved concept. This is plausible, regarding the recent budget data of 2010, where these municipalities are mostly listed as overindebted or with a non-approved budget consolidation concept.

The knowledge of citizens is expressed by the educational school level as the share of population of principal residence with highest school education level (secondary school or higher) in 2009 according to the State office for Information and Technology NRW. There is a lack of data regarding the awareness of people in NRW concerning climate change related adaptive capacity. Therefore we make use of proxy indicators of the initiative of the community (mainly driven by personal motivations) with respect to three climate change or sustainability issues. First, the participation in the network of Municipal Climate Concepts (Netzwerk Kommunale Klimakonzepte) is considered. It supports aims at development of integrated mitigation and adaptation concepts with potential funding of the Environmental Ministry NRW. We classified the municipalities as follows, the number in brackets indicate the number of municipalities falling into the respective category: all participants (38)= 1, municipalities chosen for further funding (5) =2, winners (2) = 3. Second, we considered the participation in the European Energy award with state funding according to the Energy Agency of NRW. Analogously to the preceding initiative we chose the following classification: all participants (63) = 1, municipalities with award (29) = 2, municipalities with gold award (6) = 3. Third, we took into account Agenda 21 initiatives of municipalities according to the Agenda 21 Forum (Agenda 21 Forum, 2005) and assigned these the values of 1 (238 in total). We then add the values of all indicators expressing the level of initiatives.

We average the two indicators for economic resources and knowledge and awareness respectively by applying equal weights. Also the indicator of economic resources has been aggregated with equal weight with the indicator of knowledge and awareness to the final indicator of relative adaptive capacity. In this process, all indicators were normalized by the minimum and maximum value within NRW. Thus, an equal influence of economic resources and knowledge and awareness on the human adaptive capacity is assumed.

Results for sector-specific impacts

Figure A.1 summarizes the sector-specific for both climate model applied, CCLM and REMO.

Results for total impacts considering unequal weighting factors

To analyze the influence of the weighting factors on the results of the total impacts, unequal factors have been considered additionally (physical 0.21, social 0.18, environmental 0.34 and economic 0.27) based on Greiving et al. (2011a). Figure A.2 displays the spatial distribution of the total impacts regarding the application of the unequal factors and compared the overall value distribution between the two different weighting approaches.

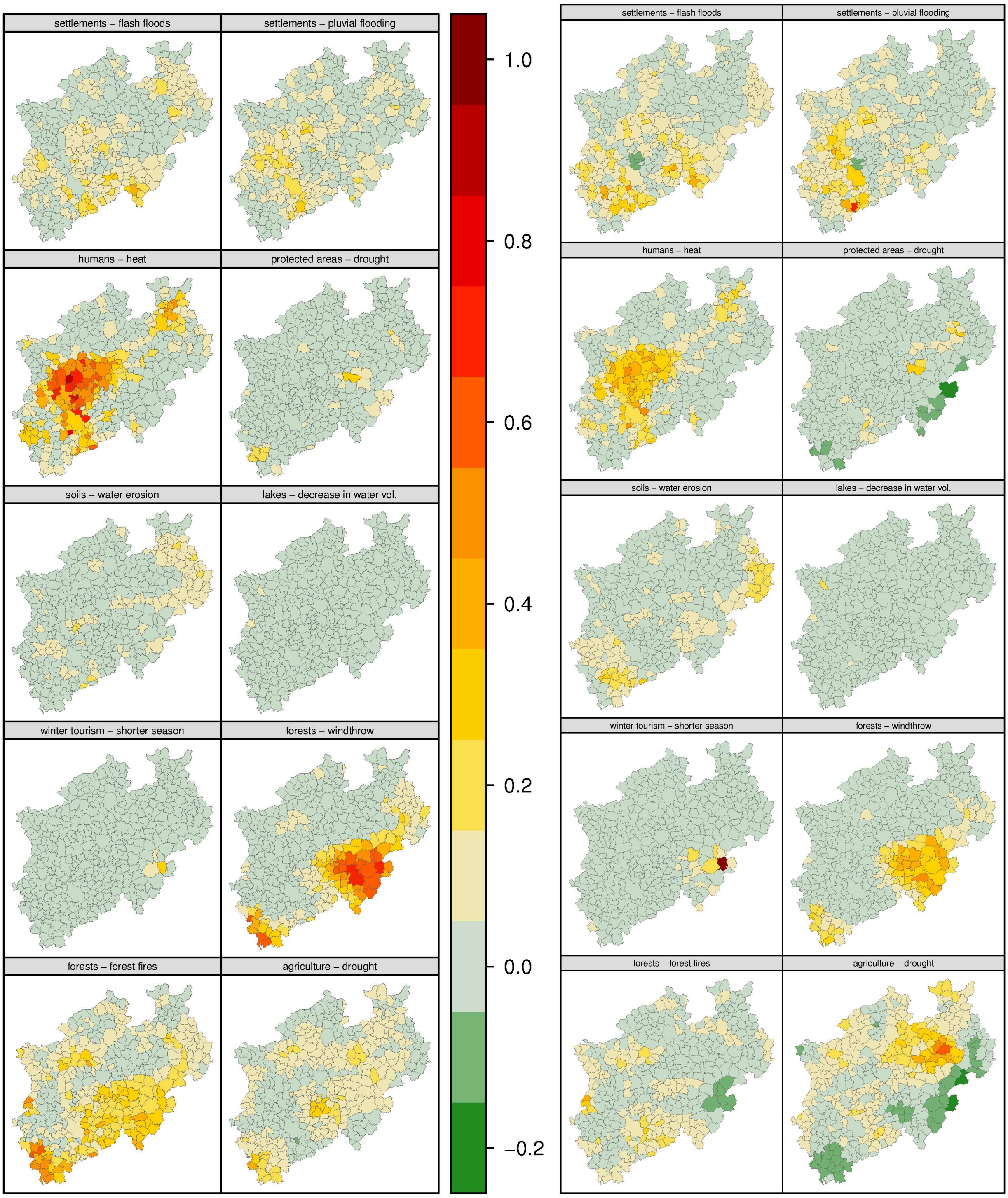

Figure A.1: Sector-specific impacts according to the climate model CCLM (left) and REMO (right). The underlying exposure is represented by changes in climatic variables between 1961-1990 and 2071-2100 under scenario A1B.

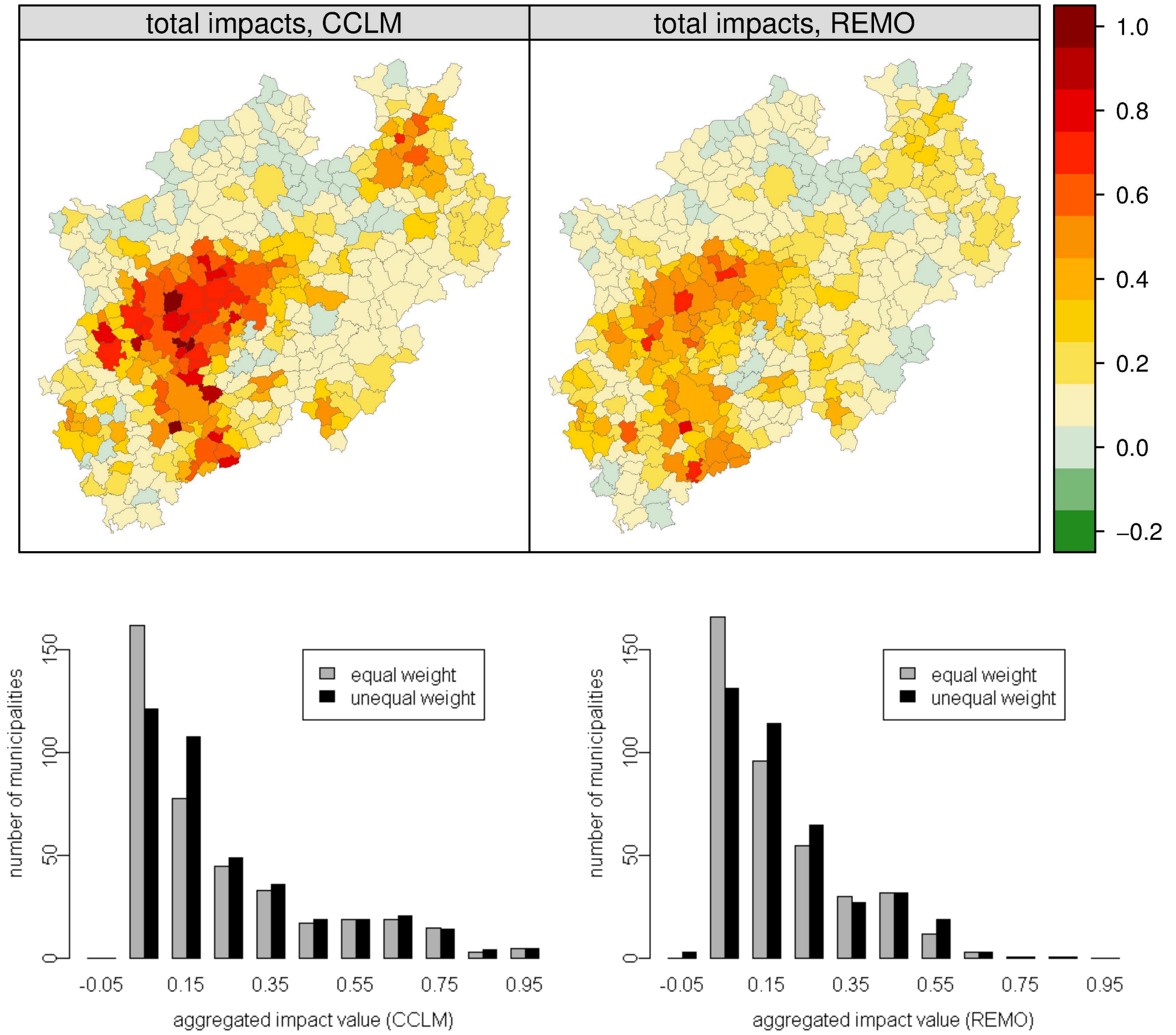

Figure A.2: Results for the total impacts taking into account unequal weighting factors (top) and comparison of the distribution of the total impacts values over municipality regarding the two different weighting factors.

Appendix B: Supplementary Material to Chapter 4

Calculation of Evapotranspiration after Turc/Ivanov:

The evapotranspiration required for the Baumgartner Index was calculated based on the Turc/Ivanov method (Turc, 1961; Wendling and Schellin, 1986) as follows:

Approach by Turc for: $T \geq 5°C$

$$ETP = 0.0031(G + 209.4)\frac{T}{T + 15}ETPF \quad (7.1)$$

Approach by Ivanov for: $T < 5°C$

$$ETP = 0.000036(T + 25)^2(100 - RH) \quad (7.2)$$

Where:

G= global radiation in Jcm^2d^1

ETPF = empririal factor for each month (0.7; 0.85; 0.95; 1.05; 1.25; 1.15; 1.05; 0.95; 0.9; 0.8; 0.75; 0.7)

T= daily mean temperature in $°C$

RH= Relative humidity in %

Results for correlation of meteorological variables and fire danger indices with area burnt

The following table summarizes the results from the correlation analysis (using Spearman's ranked correlation test) between monthly data on area burnt of German Federal States with the considered fire danger indices and raw meteorological variables.

Correlation analysis for different thresholds of relative humidity

The figure below shows correlation values between monthly forest fire data for all considered 13 states and mean relative humidity values, for different thresholds of relative humidity, for the years 1993-2010. Thus, if monthly number of days with relative humidity below 70 % is used as independent variable, a maximum correlation coefficient of -0.72 is obtained.

Analysis of the performance of indices and relative humidity for daily forest fire data of Brandenburg

The robustness of the results obtained by the Spearman's ranked correlation coefficient was tested by applying further methods for daily data from the state of Brandenburg for the years 1993-2010. This was based on the analysis of presence and absence data, i.e. the reproduction of the temporal pattern of fire days. The available fire data includes information on the amount of fires on a particular day in this state. Within the considered fire season from March to October, fires occurred on 38% of the days. Due to this large share, we selected a higher threshold, 5 fires per day, to define a "fire day". As the analysis is based on daily data, unclassified fire danger values were applied. These are available for the Angström, Nesterov and FWI indices, whereas the algorithms for the Baumgartner and modified M-68 inheritably include a classification procedure. Figure A.4 provides the results for the performance analysis based on the ranked percentile curve after Eastaugh et al. (2012) and the ROC curve (Receiver Operation Characteristic) based on the R-Package ROCR (Sing et al., 2009). The results show a similar performance of the Angström, FWI and relative humidity. For both approaches a weaker performance is apparent for the Nesterov index.

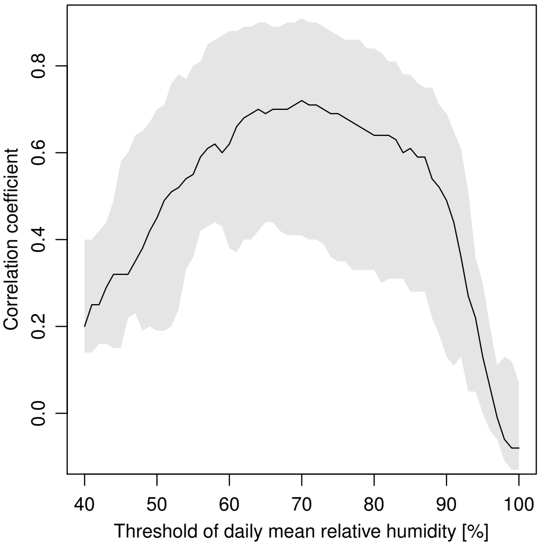

Figure A.3: Spearmans correlation coefficients (ρ) for monthly number of fires with monthly number of days below a certain threshold of daily mean relative humidity [%]. The black line represent the median, the grey area the lower and upper bounds of all 13 states.

Table A.1: Spearmans' correlation coefficients (ρ) between area burnt and meteorological variables as well as fire danger indices at state level from 1993 to 2010. Index mean values are considered as well as number of days per months falling into different categories of danger classes. ρ values were significant at the 95% confidence interval except for those in italics.

	BW	BY	BB	HE	MV	NI	NW	RP	SL	SN	ST	SH	TH	Median
Tmax	*0.12*	*0.12*	0.41	*0.16*	0.33	0.37	0.19	0.36	*0.02*	0.29	0.4	0.33	0.28	0.29
Tmean	*0.08*	*0.08*	0.36	*0.12*	0.27	0.32	*0.14*	0.33	*-0.02*	0.25	0.34	0.31	0.23	0.25
Prec.	-0.29	-0.17	-0.29	-0.32	-0.3	-0.32	-0.26	-0.25	-0.19	-0.3	-0.23	-0.18	-0.27	-0.27
Rel. hum.	-0.43	-0.68	-0.86	-0.62	-0.78	-0.71	-0.64	-0.53	-0.37	-0.72	-0.75	-0.42	-0.65	-0.65
Ang.(5)	0.18	0.29	0.67	0.42	0.54	0.51	0.42	0.41	0.24	0.51	0.61	0.39	0.49	0.42
Ang.(4-5)	0.24	0.42	0.7	0.45	0.64	0.53	0.44	0.46	0.24	0.58	0.63	0.39	0.54	0.46
Ang.(3-5)	0.3	0.45	0.69	0.45	0.66	0.61	0.47	0.51	0.22	0.6	0.64	0.47	0.56	0.51
Ang.(2-5)	0.29	0.4	0.61	0.36	0.55	0.59	0.41	0.46	*0.14*	0.51	0.56	0.39	0.45	0.45
Ang. (av.)	0.3	0.45	0.69	0.45	0.62	0.63	0.47	0.51	0.22	0.58	0.64	0.43	0.54	0.51
Ba.(5)	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	*NA*	NA
Ba.(4-5)	0.18	0.33	0.35	0.24	0.28	0.27	0.21	0.23	0.22	0.45	0.28	*0.05*	0.32	0.27
Ba.(3-5)	0.34	0.52	0.65	0.6	0.63	0.47	0.51	0.36	0.49	0.58	0.53	0.2	0.52	0.52
Ba.(2-5)	0.45	0.63	0.7	0.61	0.62	0.57	0.54	0.44	0.4	0.63	0.6	0.27	0.48	0.57
Ba. (av.)	0.44	0.64	0.72	0.63	0.66	0.57	0.56	0.43	0.45	0.66	0.63	0.27	0.53	0.57
Ne.(5)	*0.15*	0.21	0.34	0.24	0.18	*0.09*	*0.14*	*0.14*	0.19	*0.06*	0.24	*0.09*	*0.14*	0.15
Ne.(4-5)	0.32	0.26	0.58	0.42	0.45	0.36	0.34	0.4	0.24	0.45	0.55	0.32	0.46	0.4
Ne.(3-5)	0.34	0.22	0.54	0.38	0.51	0.48	0.34	0.39	0.25	0.46	0.5	0.37	0.44	0.39
Ne.(2-5)	0.31	0.2	0.48	0.31	0.45	0.46	0.33	0.4	0.22	0.45	0.41	0.29	0.34	0.34
Ne. (av.)	0.34	0.24	0.57	0.4	0.52	0.51	0.36	0.43	0.26	0.5	0.52	0.36	0.46	0.43
M-68 (5)	*NA*	*NA*	0.49	*NA*	*NA*	*NA*	*NA*	*NA*	*0.15*	*NA*	*NA*	*NA*	*NA*	0.32
M-68(4-5)	0.33	0.38	0.59	0.3	0.43	0.3	0.23	0.27	0.39	0.41	0.42	*0.13*	0.31	0.33
M-68(3-5)	0.33	0.49	0.69	0.43	0.63	0.55	0.37	0.37	0.41	0.63	0.61	0.23	0.47	0.47
M-68(2-5)	0.46	0.62	0.74	0.64	0.72	0.63	0.6	0.5	0.5	0.69	0.67	0.32	0.62	0.62
M-68 (av.)	0.46	0.63	0.77	0.64	0.73	0.62	0.61	0.5	0.5	0.71	0.69	0.32	0.63	0.63
FWI (5)	*0.15*	*NA*	*0.14*	*NA*	*NA*	*NA*	*NA*	*NA*	0.25	*0.1*	*0.13*	*NA*	*0.14*	0.14
FWI (4-5)	0.39	0.29	0.67	0.42	0.47	0.33	0.33	0.46	0.32	0.43	0.57	0.43	0.45	0.43
FWI (3-5)	0.34	0.41	0.71	0.45	0.7	0.57	0.42	0.5	0.24	0.63	0.64	0.47	0.51	0.5
FWI (2-5)	0.37	0.44	0.64	0.43	0.62	0.59	0.45	0.47	0.24	0.54	0.59	0.42	0.52	0.47
FWI (av.)	0.37	0.45	0.69	0.46	0.65	0.6	0.45	0.49	0.26	0.58	0.62	0.45	0.54	0.49

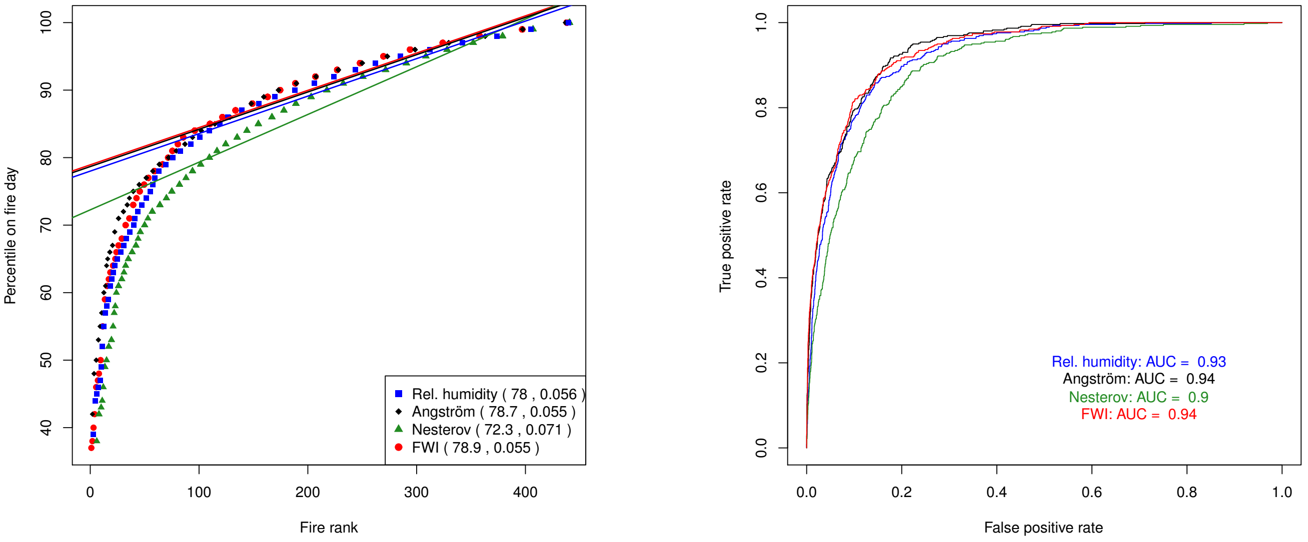

Figure A.4: Performance of fire danger indices and relative humidity regarding the temporal pattern of daily fire data for Brandenburg from 1993-2010. Left: Ranked percentile curve for the Angström, Nesterov, FWI indices and the relative humidity values. The method is applied from Eastaugh et al. (2012). Values for the intercept of the slope of the linear curves are provided in the figure. Right: ROC curve for the Angström, Nesterov, FWI indices and the relative humidity values. The corresponding AUC values are provided in the figure.

Appendix C: Supplementary Material to Section 5.2

Table A.2: Correlation coefficients of the analyzed annual input values to the model SWIM (for the years 1951-2003).

	sw	rad.	hum.	prec	tmin	tmax	tmean	clay	silt	sand	SC	por	FC	AWC	be	hi	to	tb	blai	dlai	almn	sla	hun	CN
sw	1	-0.16	0.13	0.16	-0.05	-0.1	-0.09	-0.05	0.29	-0.22	-0.08	0.47	0.72	0.31	0.08	-0.38	0.41	0.37	-0.13	0.37	0.03	0.26	-0.29	0.01
rad.	-0.16	1	-0.71	-0.52	0.25	0.62	0.49	-0.01	-0.01	0.01	0.01	-0.01	-0.01	0	0	0	0	0	0	0	0	0	0	0
hum.	0.13	-0.71	1	0.44	-0.31	-0.57	-0.49	0.08	0.04	-0.06	-0.04	0.04	0.02	0.04	0.02	0	0	0	0.01	0	0	0.01	0	0
prec	0.16	-0.52	0.44	1	0.04	-0.24	-0.12	-0.03	-0.02	0.02	0.02	-0.02	-0.01	-0.02	-0.01	-0.01	0	0	0	0	0	0	0	-0.01
tmin	-0.05	0.25	-0.31	0.04	1	0.82	0.93	-0.04	-0.02	0.03	0.03	-0.02	-0.01	-0.01	-0.01	0	0	0	0	0	0	0	0	-0.02
tmax	-0.1	0.62	-0.57	-0.24	0.82	1	0.95	-0.06	-0.02	0.03	0.03	-0.02	-0.01	-0.03	-0.01	0	0	0	-0.01	0	-0.01	-0.01	0	-0.01
tmean	-0.09	0.49	-0.49	-0.12	0.93	0.95	1	-0.05	-0.02	0.03	0.03	-0.02	-0.01	-0.01	-0.01	0	0	0	0	0	0	0	0	-0.02
clay	-0.05	-0.01	0.08	-0.03	-0.04	-0.06	-0.05	1	0.83	-0.91	-0.81	0.79	0.56	0.72	0.05	0.01	-0.01	0	0.03	0	0.01	-0.01	0	0.09
silt	0.29	-0.01	0.04	-0.02	-0.02	-0.02	-0.02	0.83	1	-0.99	-0.7	0.86	0.77	0.8	0.05	0.01	0	0.01	0.04	0	0.01	-0.01	0	0.15
sand	-0.22	0.01	-0.06	0.02	0.03	0.03	0.03	-0.91	-0.99	1	0.75	-0.87	-0.75	-0.81	-0.05	-0.01	0	-0.01	-0.04	0	-0.01	0.01	0	-0.14
SC	-0.08	0.01	-0.04	0.02	0.03	0.03	0.03	-0.81	-0.7	0.75	1	-0.77	-0.6	-0.41	-0.03	-0.01	0.02	0.01	-0.04	0.01	-0.01	0.01	-0.01	-0.22
por	0.47	-0.01	0.04	-0.02	-0.02	-0.02	-0.02	0.79	0.86	-0.87	-0.77	1	0.94	0.73	0	-0.23	0.18	0.13	-0.09	0.14	0.12	0.17	-0.07	0.03
FC	0.72	-0.01	0.02	-0.01	-0.01	-0.01	-0.01	0.56	0.77	-0.75	-0.6	0.94	1	0.69	-0.02	-0.3	0.23	0.15	-0.13	0.17	0.14	0.22	-0.09	0.02
AWC	0.31	0	0.04	-0.02	-0.01	-0.03	-0.01	0.72	0.8	-0.81	-0.41	0.73	0.69	1	0.04	0	0.01	0.01	0.01	0.01	0.02	0	-0.01	-0.06
be	0.08	0	0.02	-0.01	-0.01	-0.01	-0.01	0.05	0.05	-0.05	-0.03	0	-0.02	0.04	1	0.19	0.37	0.63	0.57	0.53	-0.46	-0.19	-0.69	0.19
hi	-0.38	0	0	-0.01	0	0	0	0.01	0.01	-0.01	-0.01	-0.23	-0.3	0	0.19	1	-0.76	-0.51	0.5	-0.57	-0.43	-0.73	0.29	0.23
to	0.41	0	0	0	0	0	0	-0.01	0	0	0.02	0.18	0.23	0.01	0.37	-0.76	1	0.9	-0.29	0.97	-0.06	0.51	-0.84	0.08
tb	0.37	0	0	0	0	0	0	0	0.01	-0.01	0.01	0.13	0.15	0.01	0.63	-0.51	0.9	1	-0.03	0.94	-0.24	0.31	-0.91	0.07
blai	-0.13	0	0.01	0	0	-0.01	0	0.03	0.04	-0.04	-0.04	-0.09	-0.13	0.01	0.57	0.5	-0.29	-0.03	1	-0.17	-0.57	-0.12	0.01	-0.18
dlai	0.37	0	0	0	0	0	0	0	0	0	0.01	0.14	0.17	0.01	0.53	-0.57	0.97	0.94	-0.17	1	-0.23	0.37	-0.95	0.19
almn	0.03	0	0	0	0	-0.01	0	0.01	0.01	-0.01	-0.01	0.12	0.14	0.02	-0.46	-0.43	-0.06	-0.24	-0.57	-0.23	1	0	0.43	-0.29
sla	0.26	0	0.01	0	0	-0.01	0	-0.01	-0.01	0.01	0.01	0.17	0.22	0	-0.19	-0.73	0.51	0.31	-0.12	0.37	0	1	-0.15	-0.17
hun	-0.29	0	0	0	0	0	0	0	0	0	-0.01	-0.07	-0.09	-0.01	-0.69	0.29	-0.84	-0.91	0.01	-0.95	0.43	-0.15	1	-0.31
CN	0.01	0	0	-0.01	-0.02	-0.01	-0.02	0.09	0.15	-0.14	-0.22	0.03	0.02	-0.06	0.19	0.23	0.08	0.07	-0.18	0.19	-0.29	-0.17	-0.31	1

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Author's declaration

I prepared this dissertation without illegal assistance. The work is original except where indicated by special reference in the text and no part of the dissertation has been submitted for any other degree. This dissertation has not been presented to any other University for examination, neither in Germany nor in another country.

Anne Holsten
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