Assessment of Impacts of Extreme Winter Storms on the Forest Resources in Baden-Württemberg - A Combined Spatial and System Dynamics Approach

Zur Erlangung des akademischen Grades eines

Doktors *der Wirtschaftswissenschaften*

(*Dr. rer. pol.*)

von der Fakultät für Wirtschaftswissenschaften

des Karlsruher Instituts für Technologie (KIT)

genehmigte

DISSERTATION

von

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Tag der mündlichen Prüfung:	08.07.2016
Referent:	Prof. Dr. Ute Werner
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Karlsruhe	21.11.2016

Acknowledgement

First of all, I would like to express my profound gratitude to my thesis supervisor Prof. Dr. Ute Werner for her excellent guidance, patience, granting the consent to explore the research topics on my own, as well as providing thoughtful advice throughout the long journey of this thesis. I am also grateful to Prof. Dr. Ute Karl for providing suggestions on the improvement of the manuscript and agreeing to co-supervise the thesis.

I wish to further thank numerous present and past colleagues in the European Institute for Energy Research (EIFER) and Électricité de France (EDF SA) for their encouragement and support. My particular gratitude towards Ludmilla Gauter, Nurten Avci, Andreas Koch, Jean Copreaux, Pablo Viejo for their belief in me and allowing me to attend seminars at the university, as well as allocating dedicated time to work on the thesis. Susanne Schmidt, Francisco Marzabal gave valuable insights into the system dynamics modelling approach and its formulation, for which I am extremely grateful. I would like to direct my gratitude to all the students with whom I have worked with, especially Eric Reed, who provided essential contributions into the vulnerability assessment.

My sincere gratitude extends to Herr Bernd Struck, deputy head of the Forest Department of the city of Karlsruhe and senior forester in Karlsruhe Bergwald, and his colleagues, who gave valuable insights into the practical aspects of forest management and salvage operations observed in the state of Baden-Württemberg. His support came through many other ways, e.g., organising a field trip to the storm affected areas in the Northern Black Forest, participation in workshops, and providing related data. Furthermore, during visits to the Forest Department of the district Freundenstadt and Gaiser Karl & Sohn GmbH in Baiersbronn, they also explained the practical insights into the regional wood flows, wood market and prices, for which I am very thankful.

I am grateful to all the members of the NatKat group of KIT, especially Dietmar Borst, for their valuable suggestions into this multi-disciplinary research topic. I would like to thank Dr. Axel Albrecht and Prof. Dr. Ulrich Kohnle of the Forest Research Institute of Baden-Württemberg (FVA) for their recommendations on modelling of windthrow vulnerability, as well as PD Dr. Michael Kunz of the Institute for Meteorology and Climate Research, KIT and Tomas Hoffherr of Munich Re Group for explaining the issues related to the winter storm hazard modelling and allowing to use related data. Furthermore, I warmly thank Emma Alice Smith for proof-reading the manuscript.

I extend sincere gratefulness to my family members and friends for their continuous inspiration and unconditional assistance throughout my life, so far.

Finally, I would like to express my heartfelt gratitude to my wife Mahfuza Murshed for her patience and support to complete the thesis.

Dedication

I would like to dedicate this thesis to my parents, both of whom rest in peace since 2014.

Abstract

This research investigates the impacts of extreme winter storms on the forest resources in the federal state of Baden-Württemberg in Germany. Such analyses can help private and public forest owners to identify whether and how much of their forest is vulnerable. It also allows them to understand what possible economic consequences might arise as a result of their decisions on forest management and salvage operations, considering the subsequent market conditions after the storm.

A standing forest provides a wide variety of direct and indirect benefits to society. It is of paramount importance for climate protection, as it supplies renewable wood materials that contribute to the transition to renewable energies (*Energiewende* in Germany) and absorbs carbon dioxide. However, extreme events, e.g., winter storms occur with greater intensity than before, which may cause increased associated costs of forest management. Forests in Baden-Württemberg have been hit by extreme winter storms which damaged the trees, destroyed roads and other infrastructure.

Appropriate decision support tools, considering a combination of space and time, are largely missing in forest management practices. Such accessible knowledge would help the decision makers to evaluate their strategic decisions in the aftermath of a storm. In this regard, development of a combined spatial and system dynamics modelling approach can help to synthesize and advance theories of forest economics, as well as simulate forest management related practices in order to analyse the impacts of extreme winter storms on forest resources. Within this research, two models are therefore developed, in order to achieve these objectives.

The first Weight of Evidence (WofE) model is based on a combined Geographic Information System (GIS) and statistical analyses to illustrate the most vulnerable forest areas in the federal state of Baden-Württemberg. Multiple model runs with different combinations of factors are performed to evaluate and validate the reliability of the results.

The outcome of the WofE model is used as an input into a system dynamics model - which is based on dynamic feedback structures and economic theories - to evaluate the economic impacts of a stochastic winter storm, under different forest management and salvage operation decisions. The model is able to demonstrate the changes in impacts over time across all of the districts, as the model components constantly evolve due to previous feedback actions and conditions.

The most significant WofE-model (M8) identifies that the soil type, forest type, topographic exposure in the direction of west and gust wind speed greater than 35 m/s are the most important determinants in windthrow assessment. The WofE methodology produces a raster grid with cells in a one ha unit area representing the posterior probabilities of damage due to a stochastic winter storm for approximately 14 million ha of forests in the state of Baden-Württemberg. About 18% of the forest area is identified as highly vulnerable, whereas 20% of the area lies within the moderately vulnerable areas. However, the majority of the forests (62%) are within the lowest vulnerable areas. In terms of spatial patterns, the forests towards the west - where topographic exposure values are high, soil is acidic and forests are coniferous - are mostly vulnerable. The districts of Calw, Freudenstadt, Breisgau-Hochschwarzwald, Ortenaukreis and Schwarzwald-Baar-Kreis are found to be the most vulnerable districts in Baden-Württemberg.

The system dynamics modelling approach is formulated considering the state of the art of modelling paradigms and a theoretical framework. The forestry sector is divided into five submodels (regarding salvage price, salvage value, standing timber value, forest clearing area value, and pre-storm timber value submodel) and the reference simulations of these submodels are run in all the 44 districts in Baden-Württemberg. The reference simulation runs aim to promote an understanding of the dynamic properties of the multidimensional and interdisciplinary aspects of the model, since different districts accommodate varying forest resources and are impacted differently by the stochastic winter storm. The net value i.e., positive or negative cash flows, in these submodels or in total, can thus be calculated and compared - at different simulation years or by discounting back the future values at present time.

Two policy based scenarios - immediate salvage operation and delayed salvage operation - are proposed to ascertain the likely impacts due to alternative salvage operation strategies. The immediate salvage operation proves to be profitable, compared to the reference scenarios and delayed salvage operation. However, the delayed salvage operation policy offers environmental and ecological benefits which are difficult to quantify in terms of monetary values. Yet, it is evident that although the extreme storm initially offers positive cash flows, it has a long term negative impact.

The model is also validated with a set of structural and behaviour tests, as suggested by the system dynamics literature and best practices. Finally, four sensitivity analyses are performed to identify the effect of some of the most important parameters. The price elasticity of demand and the discount rate selected showed significant influence on the model results. For example, an increase of demand elasticity from -0.5 to +0.5, reduces the salvage price by around 67% in the fourth year, and a decrease of elasticity to -1 increases the price by 20%.

Therefore, knowing the possible future impacts, private and public forest owners and decision makers would be able to organize marketing strategies in order to control the sale of salvage timber and to prevent the depreciation of its value. The models developed in this research are meant to be used as a learning tool, and are not predictive. Forest officers can use them as decision support tools to optimize their forest management plan for ten years or more. Moreover, the proposed models and the tool can serve to build individual scenarios as they are scalable in terms of time and space - i.e., they can be adapted to other regions and time scales - and they can be further improved, with more detailed data and input parameters.

Kurzfassung

Diese Forschungsarbeit untersucht die Auswirkungen von extremen Winterstürmen auf die Waldressourcen im Bundesland Baden-Württemberg in Deutschland. Eine solche Analyse kann den privaten und öffentlichen Waldbesitzern dabei helfen zu identifizieren, ob und welcher Anteil ihres Waldes gefährdet ist. Ebenfalls ermöglicht diese Arbeit ihnen zu verstehen, welche möglichen wirtschaftlichen Folgen aufgrund ihrer Entscheidungen über die Waldbewirtschaftung und Sturmholzverwertung entstehen könnten, unter Berücksichtigung der Marktbedingungen nach dem Sturm.

Ein stehender Wald bietet eine Vielzahl von direkten und indirekten Vorteilen für die Gesellschaft. Er ist von größter Bedeutung für den Klimaschutz, da er erneuerbare Holzmaterialien liefert, die zur Energiewende in Deutschland durch Kohlendioxidabsorption beitragen. Inzwischen treten Extremereignisse, zum Beispiel Winterstürme, jedoch mit größerer Intensität auf als zuvor. Diese könnten die mit der Forstverwaltung verbundenen Kosten erhöhen. Wälder in Baden-Württemberg sind bereits durch extreme Winterstürme getroffen worden, die Bäume beschädigten und Straßen sowie andere Infrastrukturelemente zerstörten.

Werkzeuge zur Entscheidungsunterstützung, mit einer kombinierten Berücksichtigung von Raum- und Zeit, fehlen noch weitgehend in der praktizierten Waldbewirtschaftung. Ein solches Wissen würde den Entscheidungsträgern helfen, ihre strategischen Entscheidungen in der Zeit nach einem Sturm zu bewerten. In dieser Hinsicht kann die Entwicklung eines kombinierten räumlichen und systemdynamischen Modellierungsansatzes dazu beitragen, Theorien der Forstökonomie weiterzuentwickeln, sowie die praktische Forstverwaltung zu simulieren, um die Auswirkungen von extremen Winterstürmen auf die Waldbestände zu analysieren. Innerhalb dieser Forschungsarbeit werden deshalb zwei Modelle entwickelt, um die genannten Ziele zu erreichen.

Das erste Weight-of-Evidence-Modell (WofE-Modell) basiert auf einem kombinierten Geoinformationssystem (GIS) und statistischen Analysen um die am meisten gefährdeten Waldgebiete des Bundeslandes Baden-Württemberg zu veranschaulichen. Mehrere Modellläufe mit unterschiedlichen Kombinationen von Faktoren werden durchgeführt, um die Ergebnisse auszuwerten und zu validieren.

Das Ergebnis des WofE-Modells wird als Input in einem System-Dynamics-Modell verwendet - das auf dynamischen Rückkopplungsstrukturen und ökonomischen

Theorien basiert – um die wirtschaftlichen Auswirkungen eines stochastischen Wintersturmes zu bewerten, unter verschiedenen Forstverwaltungs- und Sturmholzverwertungsentscheidungen. Das Modell ist in der Lage, einerseits die Veränderungen der Auswirkungen im Laufe der Zeit in allen Land- und Stadtkreisen aufzuzeigen, aber auch wie sich die Modellkomponenten ständig aufgrund früherer Feedback-Aktionen und Bedingungen entwickeln.

Das signifikanteste WofE-Modell (M8) identifiziert, dass der Bodentyp, Waldtyp, die topographische Exposition in Richtung Westen und eine Windstoßgeschwindigkeit von mehr als 35 m/s die wichtigsten Determinanten für die Beurteilung des Windwurfes sind. Die WofE-Modell erzeugt ein Raster mit Zellen von einem Hektar Fläche, mit posteriori Wahrscheinlichkeiten der Beschädigung durch einen stochastischen Wintersturm für die rund 14 Millionen Hektar Wald im Bundesland Baden-Württemberg. Über 18% der Waldfläche werden als sehr anfällig identifiziert, dagegen liegt 20% der Fläche in den gemäßigt gefährdeten Gebieten. Allerdings befindet sich die Mehrheit der Wälder (62%) innerhalb der am niedrigsten gefährdeten Gebiete. Im Hinblick auf die räumliche Verteilung gilt, dass die Wälder im Westen - wo die topographische Exposition hoch ist, der Boden sauer ist und die Wälder Nadelwälder sind - am anfälligsten sind. Die Kreise von Calw, Freudenstadt, Breisgau-Hochschwarzwald, der Ortenaukreis und der Schwarzwald-Baar-Kreis sind die am stärksten gefährdeten Kreise in Baden-Württemberg.

Der System-Dynamics-Modellierungsansatz ist unter Berücksichtigung des Standes der Technik bei Modellierungsparadigmen und auf Grundlage theoretischer Rahmenbedingungen formuliert. Dabei wird die Forstwirtschaft in fünf Teilmodellen abgebildet (bezogen auf Sturmholzpreis, Sturmholzwert, Holzbestandswert, Kahlflächenwert, Holzwert vor dem Sturm) und die Referenzsimulationen dieser Teilmodelle werden für alle 44 Land- und Stadtkreise in Baden-Württemberg durchgeführt. Die Referenzsimulation fördert ein Verständnis für die dynamischen Eigenschaften der multidimensionalen und interdisziplinären Aspekte des Modells, da verschiedene Kreise unterschiedliche Waldressourcen beinhalten und unterschiedlich von dem stochastischen Wintersturm betroffen sind. Der Nettowert, d.h. positive oder negative Cashflows, kann für jedes der Submodelle oder als Ganzes berechnet und verglichen werden – für verschiedene Simulationsjahre oder durch Diskontierung der zukünftigen Werte zum gegenwärtigen Zeitpunkt.

Zwei verschiedene strategische Szenarien – die sofortige Sturmholzverwertung bzw. eine verzögerte Verwertung – werden vorgeschlagen, um die wahrscheinlichen Auswirkungen dieser alternativen Verwertungsstrategien zu ermitteln. Die sofortige Holzverwertungsaktion erweist sich als profitabel, im Vergleich zu den Referenzszenarien und der verzögerten Verwertungsaktion. Allerdings bietet die verzögerte Verwertungsstrategie Umwelt- und ökologische Vorteile, die sich nur schwer monetär quantifizieren lassen. Es ist dennoch ersichtlich, dass, obwohl der extreme Sturm zunächst Positiven Cashflows bietet, er langfristig negative Auswirkungen hat.

Das Modell wird auch durch eine Reihe von strukturellen und Verhaltenstests validiert, wie sie in der System-Dynamics-Literatur und in bewährten Anwendungen vorgeschlagen werden. So werden vier Sensitivitätsanalysen durchgeführt, um die Auswirkungen einiger wichtiger Parameter zu identifizieren. Die Preiselastizität der Nachfrage und der gewählte Diskontsatz zeigen größe Einfluss auf für die Modellergebnisse. Zum Beispiel, führt eine Erhöhung der Preiselastizität der Nachfrage von -0.5 auf +0.5 zu einer Reduktion des Sturmholzpreises um 67% im vierten Jahr. Eine Abnahme der Elastizität auf -1 erhöht den Preis im vierten Jahr um 20%.

Durch die Kenntnis der möglichen zukünftigen Auswirkungen können die privaten und öffentlichen Waldbesitzer und Entscheidungsträger Marketing-Strategien entwickeln, um den Verkauf von Sturmholz zu steuern und und den Wertverlust zu reduzieren. Die in dieser Arbeit entwickelten Modelle sollen als Lernwerkzeug dienen. Forstbeamte können sie als Entscheidungshilfe nutzen, um ihren Waldbewirtschaftungsplan für die nächsten zehn Jahre oder mehr zu optimieren. Darüber hinaus können die vorgeschlagenen Modelle dazu dienen, einzelne Szenarien zu konstruieren, die in Bezug auf Zeit und Raum skalierbar sind und weiter präzisiert werden können. Das heißt: die Modelle können auch auf andere Regionen und Zeiträume angepasst und mit präzisierten Daten und Eingabe/Inputparametern eingesetzt werden.

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Abbreviations

AC	Agterberg-Cheng Test
AGDW	Alliance of German Forest Owner Association (*Arbeitsgemeinschaft Deutscher Waldbesitzerverbände*)
ArcSDM	Spatial Data Modeller for ArcGIS and Spatial Analyst
BMELV	Federal Ministry for Food, Agriculture and Consumer Protection (*Bundesministerium für Ernährung, Landwirtschaft und Verbraucherschutz)*
BMEL	Federal Ministry for Food and Agriculture (*Bundesministerium für Ernährung, Landwirtschaft)*
BMU	Federal Ministry for the Environment (*Bundesumweltministerium)*
BMWi	Federal Ministry for Economic Affairs and Energy (*Bundesministerium für Wirtschaft und Energie)*
CAPP	Cumulative Area Posterior Probability
CA	Cellular Automata
CI	Conditionally Independence
CLC	CORINE Land Cover data
CLD	Causal Loop Diagram
CO_2	Carbon dioxide
CORINE	Coordination of Information on the Environment
DLR	German Aerospace Center (*Deutsches Zentrum für Luft- und Raumfahrt*)
DWD	German Weather Service (*Deutscher Wetterdienst*)
EIFER	European Institute for Energy Research
EEA	European Environment Agency
EEG	Renewable Energy Law (*Erneuerbare-Energien-Gesetz*)

EEWärmeG	Renewable Energy Heat Law (*Erneuerbare-Energien-Wärmegesetz)*
EnEV	Energy Saving Regulation (*Energieeinsparverordnung*)
EU	European Union
FABW	Forest Act of Baden-Württemberg (*Landeswaldgesetz*)
FAO	Food and Agriculture Organization
FFA	Federal Forest Act (*Bundeswaldgesetz*)
FFH	Forest in Natura 2000 areas
Fm	Festmeter
FOKA	Forest Chamber Baden-Württemberg (*Forstkammer Baden-Württemberg Waldbesitzerverband e.V.*)
FVA	Forest Research Institute Baden-Württemberg (*Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg*)
GDP	Gross Domestic Product
GIS	Geographic Information System
GUI	Graphical User Interface
Ha	Hectare
HGB	German Commercial Code (*Handelsgesetzbuch*)
IO	Input-Output model
IEA	International Energy Agency
IMK	Institute of Meteorology and Climate Research (*Institut für Meteorologie und Klimaforschung*), KIT
IPCC	Intergovernmental Panel on Climate Change
KAMM	Karlsruhe Atmospheric Mesoscale Model
Km	Kilometre
KIT	Karlsruhe Institute of Technology

LUBW	State Institute for Environment, Measurements and Nature Conservation Baden-Württemberg (*Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg*)
MCPFE	Ministerial Conference on the Protection of Forests in Europe
MLR	Ministry for Rural Affairs and Consumer Protection (*Ministerium für Ländlichen Raum und Verbraucherschutz)*
NFA	National Forest Act
NFI	National Forest Inventory (*Bundeswaldinventur*)
NFP	National Forest Programme
PRC	Prediction-Rate Curve
SME	Small and Medium-sized Enterprises
SRTM	Shuttle Radar Topography Mission
SRC	Success-Rate Curve
Topex	Topographic Exposure
UBA	Federal Environmental Agency (*Umweltbundesamt*)
UNFCCC	United Nations Framework Convention on Climate Change
UNISDR	United Nations International Strategy for Disaster Reduction
USGS	United States Geological Survey
WaBoA	Water and Soil Atlas of Baden-Württemberg (*Wasser- und Bodenatlas Baden-Württemberg*)
WMO	World Meteorological Organization
WofE	Weight of Evidence

1 Introduction

1.1 Problem definition

1.1.1 Importance of forestry

1.1.1.1 Direct and indirect benefits

A standing forest[1] provides a wide variety of direct and indirect benefits to society. Some benefits, e.g., climate protection or biodiversity benefits are even external to the nation where the forest is located. It is a source of life for society and environment, as it plays an important role in maintaining the balance of the ecosystem. Human beings are both directly and indirectly facilitated with this private and social benefits of forestry and its diverse services. The direct advantages of having stocks of trees in forests are many, e.g., standing trees are seen as capital goods or assets that are invested for a long term. The biological growth of the trees will increase the harvestable volume and finally the value if other economic factors, e.g., price of timber, inflation, etc. remain stable. Besides wood, forests also supply different types of marketable products, e.g., fruits, honey, medical plants, wild animals, etc. Regionally, the value of these products may even exceed the value of timber production.

Many forest dependent industries, e.g., paper and pulp, sawmills, pellets and wood chips industries, biomass based power plants directly get raw materials (i.e., wood) from the forests. Wood can be used for multiple purposes and thus has multiple benefits. Therefore, forest dependent industries in Germany generate over 90% of their sales with wood, which is approximately three billion Euros (Dieter, 2011). The importance of wood production becomes more evident when the processing is considered. The forestry cluster (i.e., all industries relying on wood) in Germany has a turnover of approximately 170 billion Euros, which is roughly 3.4% of the overall turnover and employs around 1.2 million people (Dieter, 2011). In this way, forests

[1] Forest is defined as the vegetation dominated by plants with woody stems, which reach a mature height in excess of a few metres, while forestry is the use and management of forests to provide goods and services to people. Forest management activities are under-taken in a forest to achieve the provision of the goods and services which are desired from it (West, 2009).

generate employment and make a considerable contribution towards the national and regional economy.

Further benefits of forestry through tourism and recreational services to society are also very important. Germany is a densely populated country with over 80 million inhabitants living on 35.7 million hectares (ha) and with 32% of this area covered with forests, there is significant space for recreation and natural life (BMEL, 2014).

The indirect economic benefits of forests are also important. Many positive ecosystem services[2] delivered by the forests to society, e.g., the cleaning up of ground water, protection of settlement from natural disasters, protection of transport infrastructures and agricultural areas from erosions or avalanches, provision of wildlife habitats, allowance of the biodiversity that amass from the forest, the ability to absorb carbon dioxide (CO_2) to stop global warming is extremely important to society. Unfortunately, the values of these benefits are difficult to quantify and are often not assessed.

1.1.1.2 Renewable energy supply

The energy sector is the biggest and most dynamic branch of the German economy. With the increasing prices and demand of energy, awareness of energy security, efficiency, pollution and green-house gas emissions are also rising, which enforce scientists and policy makers to search for alternatives to traditional fossil fuel based energy options.

According to the new policy scenarios published by the International Energy Agency (IEA), energy demand worldwide will grow by 37% by the year 2040, an average annual growth rate of 1.1% (IEA, 2014). The world electricity demand will increase by almost 80% over the period of 2012-2040. The share of renewables in total power generation will rise from 21% in 2012 to 33% in 2040, as they supply nearly half of the growth in global electricity generation (IEA, 2014). Furthermore, the European Union (EU) has set a series of binding renewable energy targets for all of its Member States, e.g., 35% of Europe's electricity is projected to come from renewable sources by 2020.

After the Fukushima disaster in 2011, the Federal Republic of Germany decided to phase out from nuclear power and declared an energy transition (*Energiewende*) in order to battle against global warming and to end the reliance on nuclear power

[2] Ecosystem services are defined as the benefits that humans obtain from ecosystems. In recent years, this concept has become the paradigm of ecosystem management (Seppelt, Dormann, Eppink, Lautenbach, & Schmidt, 2011).

(Karnitschnig, 2014). Several existing laws and regulations targeting management of energy usage from renewable sources, increasing energy efficiencies (e.g., *Erneuerbare-Energien-Gesetz* (EEG), *Energieeinsparverordnung* (EnEV), *Erneuerbare-Energien-Wärmegesetz* (EEWärmeG)) have been amended in favour of this energy transition and facilitated its enforcement in Germany.

EEG (Renewable Energy Sources Act) promotes the generation of electricity using renewable energy sources. According to section 1, paragraph 2 of EEG 2014, new targets are set for renewable energy, e.g., 40% - 45% of the share in the gross electricity consumption by 2025, 55% - 60% by 2035 and 80% by 2050 (EEG, 2014). EEWärmeG (Renewable Energies Heat Act) promotes the increase of heat generated from renewable energy to 14% by 2020 (EEWärmeG, 2008).

The renewable energy sector in the Federal Republic of Germany is among the most innovative and successful worldwide. On the 11th May 2014, Germany set a new record, generating 74% of power required from renewable energy (Chabot, 2014). In recent years, the share of renewables in final energy consumption in Germany has increased from 3.7% (in 2000) to 12.4% (in 2013) and is expected to rise to 18% in 2020 (BMWi, 2015). The electricity generation from renewable energy sources has increased from 36.0 TWh (6.2% in 2000), to 143.8 TWh (23.7% in 2012) to 152.4 TWh (25.5% in 2013) (Figure 1.1).

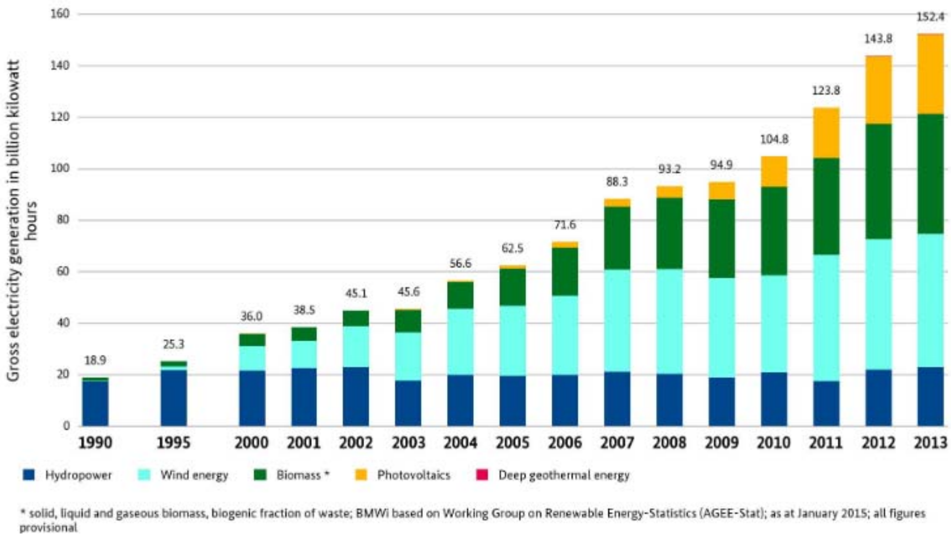

Figure 1.1: Development of electricity generation from renewable energy sources in Germany[3]

[3] (BMWi, 2015).

In 2013, approximately 30.6% of electricity was generated from the biomass. It represents an increase of 6% compared to 2012 (Figure 1.2).

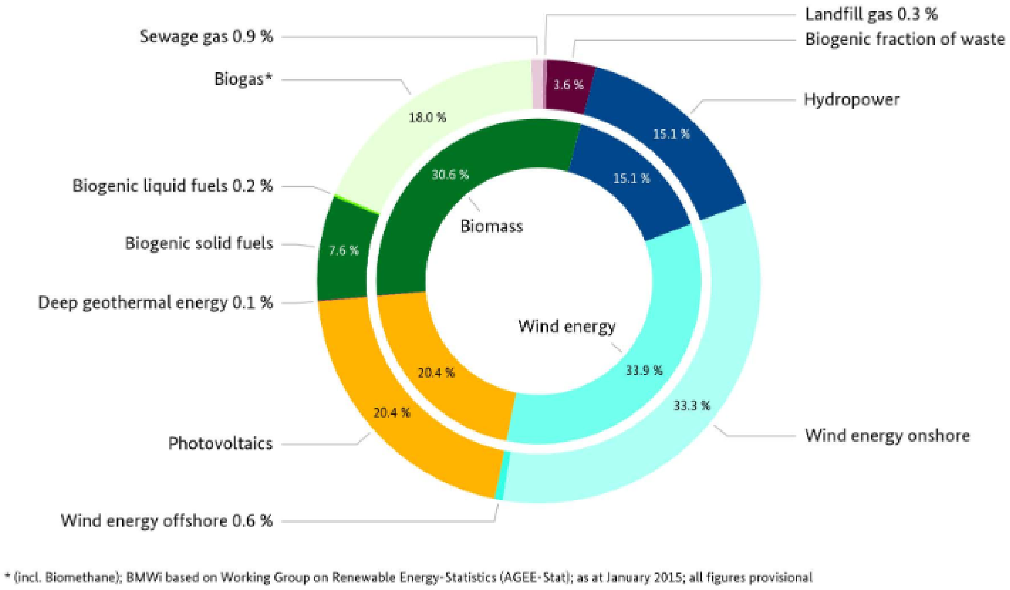

Figure 1.2: Renewables-based electricity generation in Germany 2013[4]

The share of renewable energy sources in heat consumption has also increased from 4% in 2000 to 9.6% in 2013 (Figure 1.3). From the total consumption of 137.6 TWh of heat in 2013, about 88.1% was generated from biomass (BMWi, 2015).

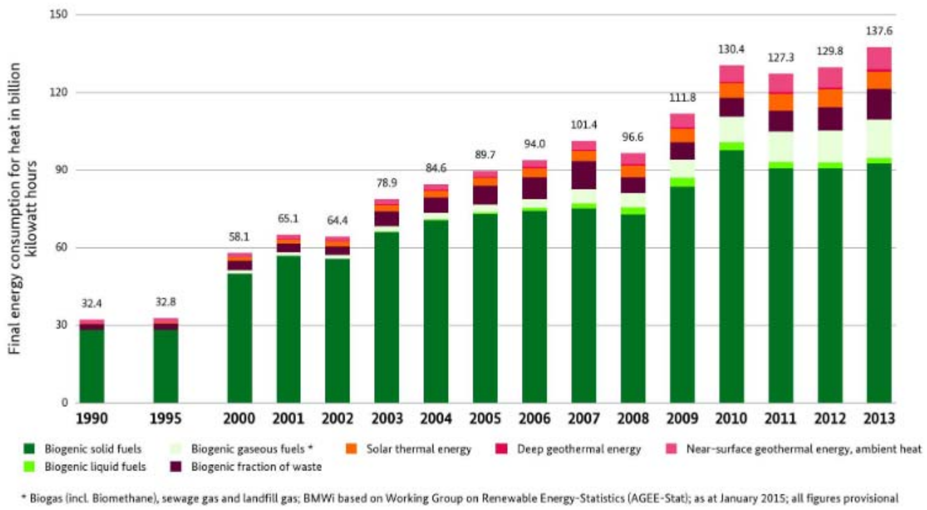

Figure 1.3: Development of heat consumption from renewable energy sources in Germany[5]

[4] (BMWi, 2015).
[5] (BMWi, 2015).

In a bio-based and more sustainability-oriented economy such as that of the Federal Republic of Germany, renewable raw materials, especially wood, are fundamental to the energy transition. Wood is replenishable, durable and versatile and has been used for millennia for different purposes – from construction and furniture-making to paper production and heating. Recently, competition between the material and energy usage of wood has increased. Currently, half of the wood harvested and removed from European forests is used for industrial processing purposes. But in Germany, the use of wood as a source of energy has increased significantly since 2004 (Figure 1.4).

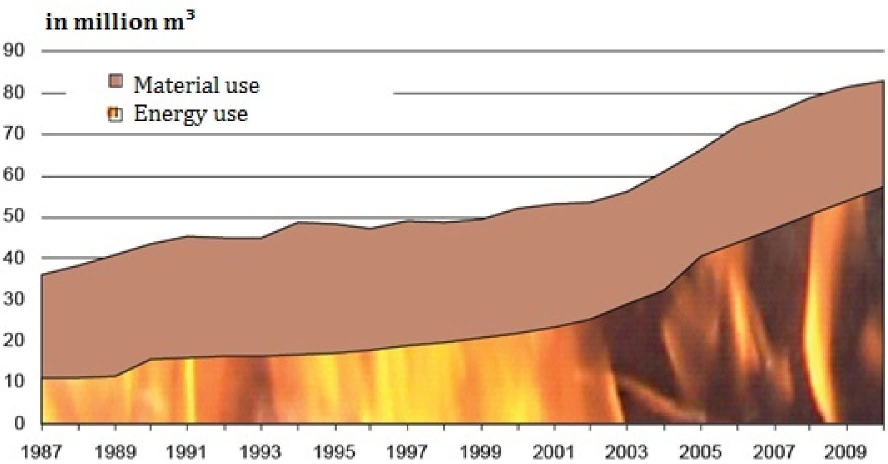

Figure 1.4: Use of wood as material and energy sources in Germany[6]

1.1.1.3 Climate protection

Greenhouse gases, e.g., CO_2 is necessary for trees' growth and is absorbed within the wood. Therefore, forests are a carbon sink and contribute globally to reduce the CO_2 content of the atmosphere (Pan et al., 2011).

The National Forest Inventory (NFI) in the Federal Republic of Germany provides the database for estimation of carbon stocks in living biomass for the observation period between 2002 and 2012. Approximately 1,169 million tons of carbon was present in living trees and in dead wood. These are roughly 150 tons of carbon per ha in the upper and below ground biomass (BMEL, 2014). Therefore, forests in Germany relieve the atmosphere annually by roughly 52 million tons CO_2 (Dunger et al., 2014) which reduces emissions by roughly 6% (BMEL, 2014).

[6] (Mantau, 2008).

1.1.1.4 Protection of nature and habitat

Protected forest areas are a means for nature conservation which constitutes a well-established and important foundation for the protection of nature and natural resources. Protected forest areas aim either to conserve forest biological diversity, i.e., the diversity of genes and species in forests and the diversity of forest ecosystems, or to protect landscapes.

According to the guidelines of the Ministerial Conference on the Protection of Forests in Europe (MCPFE), around 12% of Europe's forests are protected, of which 85% are designated to conserve forest biodiversity, while 15% are assigned to protect landscapes (MCPFE, 2003). In the Federal Republic of Germany, about 63% of the forests are labelled as protected forest area (MCPFE, 2003). However, more than 70% of the forest area in Baden-Württemberg is designated as protected areas and 11% is specified as strictly protected areas (i.e., strict forest reserves, nature protection areas, protected forest biotopes) (Spielmann, Bücking, Quadt, & Krumm, 2013).

Habitat or biotope trees are important as they contribute high ecological value to biodiversity. Habitat trees are mostly old trees with special features such as woodpeckers or nests, crown dead wood or fungal consoles. In Baden-Württemberg forests, around 6.7 million of such trees exist, with a density of 5 trees per ha. Their wood stock is nearly 13 million m^3, less than 10 m^3 per ha. They are particularly strong trees having average volume of 1.9 m^3; two thirds of them have a diameter of more than 50 cm. However, 83% of these trees are deciduous trees (Kändler & Cullmann, 2014).

1.1.2 Increasing extreme events

1.1.2.1 Statistical overview

Within a changing climate, hydro-meteorological natural hazards[7] continue to strike and are expected to increase in magnitude, complexity, frequency and, therefore, impact many parts of the world (Murshed et al., 2007). The associated cost is also increasing. In 2014, worldwide losses from natural catastrophes totalled 110 billion US$ for direct economic losses and 31 billion US$ for insured losses (MunichRe, 2015). Although in 2014 both the insured and overall losses were less than during

[7] Hazard is defined as a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage (UNISDR, 2009).

the previous two years (Figure 1.5), the ten-year average for economic losses is 190 billion US$, and for insured losses 58 billion US$, while the 30 year averages are 130 and 33 billion US$, respectively (MunichRe, 2015).

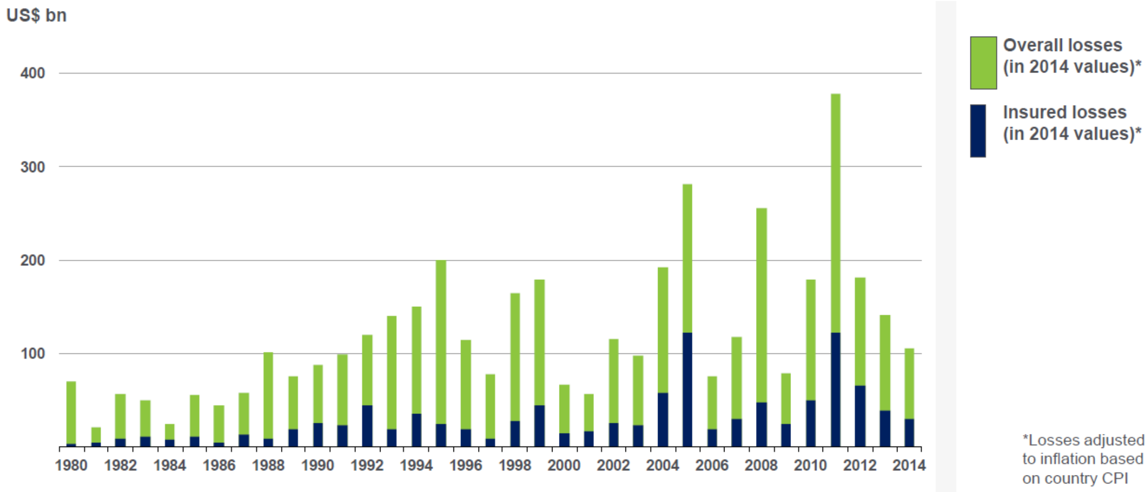

Figure 1.5: Weather related loss events worldwide 1980 – 2014, overall and insured losses[8]

Despite the reduced losses in the last two years, the frequency of extreme events is above average. Extreme events are defined as natural hazards that have increased intensity and frequency (Wisner, Blaikie, Cannon, & Davis, 2003), and cause extraordinary economic and social (loss of life or livelihood) damage (Easterling et al., 2000). Extreme events differ from natural hazards in such a way that they deviate from the average natural event and thus become remarkable as they cause severe damage. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) defines an extreme weather event as one that is rare at a particular place and/or time of year. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile of a probability density function estimated from observations. A comprehensive comparative analysis on the characteristics of different extreme events was outlined by (Menny, 2011).

Different natural hazards and extreme events make the exposed elements susceptible on different levels, therefore, their vulnerability[9] towards these events are very different. For example, forest and agricultural resources such as trees are

[8] (MunichRe, 2015).
[9] Vulnerability is defined as the degree of susceptibility of a given element or set of elements due to an extreme event or a hazard, modified after (Lewis, 1999), (Sarewitz & Pielke Jr., 2000).

particularly vulnerable to hail storms, winter storms, drought, precipitation and fire. Hail storms can clearly damage plants, especially corn but they cause little damage to forest trees. Temperature and precipitation mostly affect agriculture and bioenergy crops (e.g., willow, poplar, etc.). Winter storms might strongly damage forest wood as in the events of Vivian (1990), Lothar (1999) or Kyrill (2007).

(MunichRe, 2015) recorded 980 loss-related natural catastrophes, which is higher than the average of the last 10 and 30 years (830 and 640, respectively) (Figure 1.6). The study also explains that the storms (i.e., hail storms and thunder storms) are increasing in importance and impact, especially in various regions in the USA and central Europe.

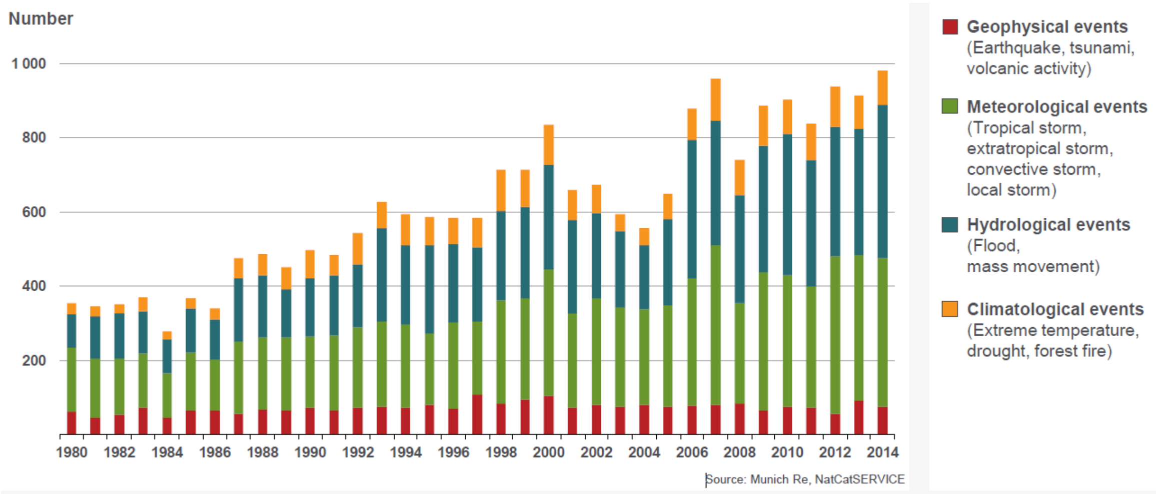

Figure 1.6: Loss events worldwide 1980 – 2014, number of events[10]

Compared to other geophysical (earthquake, tsunami, etc.), hydrological (flood) or climatological (extreme temperature, drought, etc.) events, extreme winter storms affect relatively large areas and cause considerable losses, often amounting to several billion Euros. Winter storms caused an estimated 2.3 billion US$ of insured losses in 2014, up from 1.9 billion US$ in 2013. From 1994 to 2013 winter storms resulted in about 27 billion US$ in insured catastrophic losses (MunichRe, 2015). In central Europe, the storm Kyrill in January 2007 caused insured losses exceeding 4 billion Euros, at least 46 fatalities and uprooted more than 60 million trees (Fink, Brücher, Ermert, Krüger, & Pinto, 2009). Lothar and Martin storms[11] in December 1999 in Europe, caused 19.2 billion US$ of damage to power grids and forest

[10] (MunichRe, 2015).

[11] Lothar crossed France, Belgium and Germany on 25 – 27th December 1999. Martin affected southern Europe (France, Switzerland, Spain and Italy) on 26 – 28th December 1999.

resources. Windstorm Klaus in January 2009, was responsible for around 40 million of m^3 of damages in the south-western part of France (Nicolas, 2009). Other winter storms, e.g., Wiebke and Vivian in 1990 also caused significant forest damage.

In Europe, over the period of 1950 – 2000, an annual average of 35 million m^3 wood was damaged by forest disturbances. Storms were responsible for 53% of the total damage, fire for 16%, snow for 3% and other abiotic causes for 5% (M.-J. Schelhaas, Nabuurs, & Schuck, 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).

The occurrence of extreme winter storms are inevitable in many regions. They temporally perturb ecosystem equilibrium and change the temporal and spatial structure of a landscape. Although their location, frequency or strength may vary, such storms will continue to occur worldwide (Schindler, Bauhus, & Mayer, 2012). It is reported that the current high level of storm activity will not drop considerably in future decades over southern and central Germany (Rauthe, Kunz, & Kottmeier, 2010).

1.1.2.2 Extreme winter storms in Baden-Württemberg

The state of Baden-Württemberg has been and will possibly be hit by extreme winter storms, hail, thunder storms and heavy rain in future. Other potential but very unlikely extreme events that could occur are drought, forest fire and earthquakes.

The effects of wind and wind strength are identified by the Beaufort scale which ranges from 0 (calm) to 12 (hurricane). According to this scale, wind strengths between 10 and 12, with velocities starting from 24.5 m/s are defined as ‘strong storm’ and ‘extreme storms’ (DWD, 2015). In winter, furthermore, the temperature difference between the equator and central European latitudes is significant and thus stronger winds arise. Examples of some extreme winter storms include Wiebke (1990), Lothar and Martin (1999) and Kyrill (2007).

Extreme winter storm hazard modelling and risk[12] analysis was performed in Germany by (Donat, Pardowitz, Leckebusch, Ulbrich, & Burghoff, 2011), (Heneka,

[12] Risk is the consequence resulting from the occurrence of a hazard. Risk is modelled as the function of an interaction between four basic components: (1) certain hazards, (2) elements exposed to hazardous events with specified characteristics, (3) the susceptibility of the exposed elements to the hazardous impact and (4) the resulting consequences (Borst, Jung, Murshed, & Werner, 2006), (UNISDR, 2004).

Hofherr, Ruck, & Kottmeier, 2006), (Hofherr & Kunz, 2010). For example, (Heneka, 2006) modelled the winter storm hazard in maps (Figure 1.7) displaying the spatial distribution of the maximum wind speed with an exceedance probability of 0.02 per year[13] in Baden-Württemberg. Very high wind speeds (often above 50 m/s) are modelled over low-range mountain regions and especially at the top of hills, as well as along ridges. The lowest wind speeds (below 28 m/s) are expected in the valleys of the Black Forest.

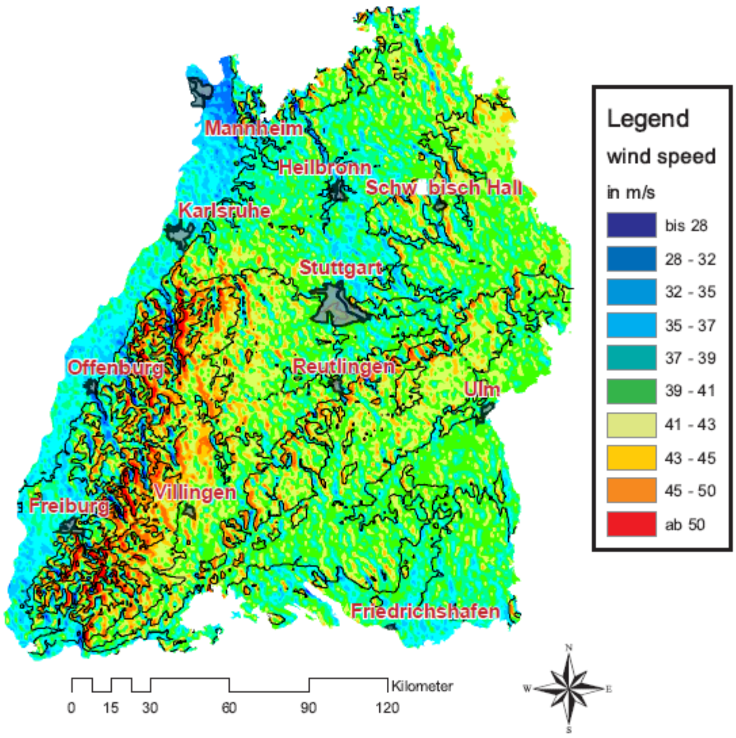

Figure 1.7: Maximum gust speeds in Baden-Württemberg with an exceedance probability of 0.02 per year[14]

Later, (Hofherr & Kunz, 2010) developed a method for the assessment of storm hazards caused by large-scale winter storms in Germany. Hazard curves, including quantification of the uncertainties, are determined for 1 km x 1 km grid points by applying extreme value statistics. Then the storm hazard maps for annual

[13] This equals a mean return period of 50 years. It is a statistical measurement typically based on historic data denoting the average recurrence interval over an extended period of time. The calculation of return period assumes that the probability of the event occurring does not vary over time and is independent of past events (Liu & Kokic, 2014).
[14] (Heneka, 2006).

exceedance probabilities of p = 0.5 and p =0.05, corresponding to return periods of 2 and 20 years, respectively, are modelled at each grid point (Figure 1.8).

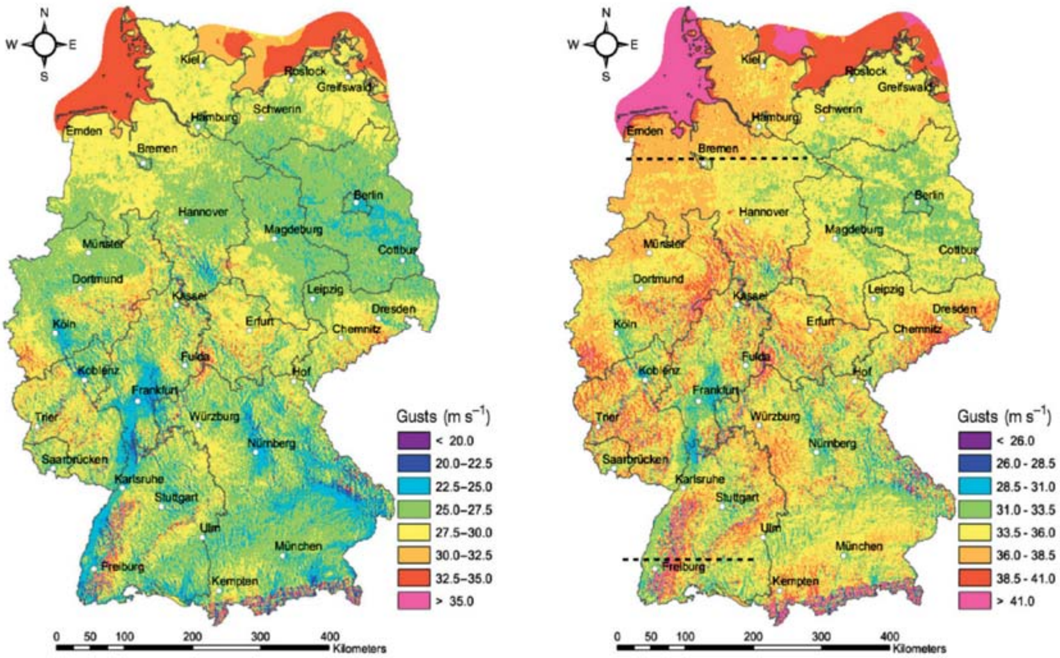

Figure 1.8: Maximum wind speeds in Germany on a 1 km × 1 km grid, with an exceedance probability of p = 0.5 (return period 2 year; left) and p = 0.05 (return period 20 year; right)[15]

In the former case, the wind speed varies between 20 and 35 m/s, whereas in the latter case, it ranges from 26 to 45 m/s. The regions that are mostly affected by high wind speeds are the North Sea coast and the crests of the low mountain ranges or the Alps. Less affected, are the regions of Brandenburg (eastern Germany), the Rhine-Main area (around Frankfurt), as well as the northern parts of Bavaria (southeastern Germany) and the southeastern parts of Baden-Württemberg (southwestern Germany) (Hofherr & Kunz, 2010).

The modelled winter storm hazard data, i.e., the wind speed at 1 km x 1 km across the state of Baden-Württemberg is considered in this research for assessing the vulnerabilities of forest resources (Chapter 3).

1.1.2.3 Climate change trends

Climate change is a global phenomenon. It exposes people, societies, economic sectors and puts ecosystems at risk. The human influence on the climate system is also clear, as recent anthropogenic emissions of greenhouse gases are the highest in

[15] (Hofherr & Kunz, 2010).

history (IPCC, 2014). According to the IPCC, climate change refers to a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity.

Warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades and millennia. The atmosphere and oceans have warmed, snow and ice have diminished, sea levels have risen, and the volume of anthropogenic greenhouse gas emissions has increased (Figure 1.9).

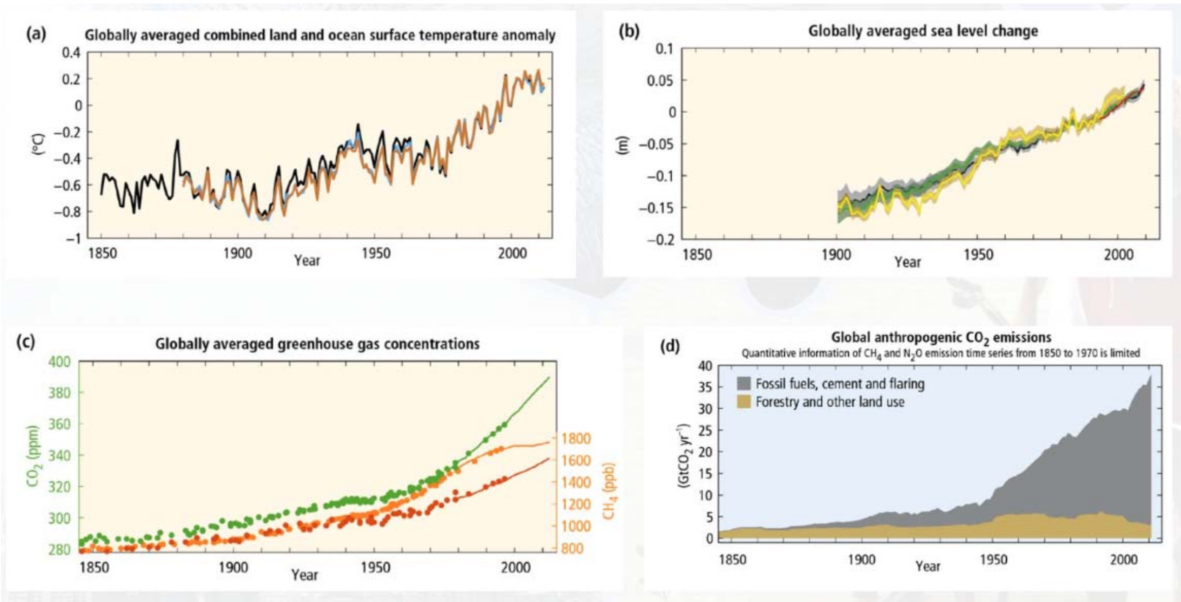

Figure 1.9: Unequivocal evidence of climate change (a) globally averaged temperature anomaly (b) globally averaged sea-level change (c) globally averaged greenhouse gas concentrations (d) global anthropogenic CO_2 emissions[16]

Global average temperatures have increased by 0.74˚C between 1906 and 2007, with the years 1995 to 2005 ranking among the warmest since instrumental observations of temperature began in 1850 (Rahmstorf et al., 2007).

The continued emission of greenhouse gases will cause further warming and long-lasting changes in all components of the climate system. Impacts from recent climate-related extremes, e.g., storms, heat waves, droughts, floods, cyclones and wildfires, reveal significant vulnerability and exposure of some ecosystems such as forests, food production and water supply and of many human systems, e.g., damage

[16] (IPCC, 2014).

to infrastructure and settlements, human morbidity and mortality, negative effects on mental health and overall human well-being, etc. (IPCC, 2014).

In identifying scenarios of future climate change in the Federal Republic of Germany, (Schröter, Zebisch, & Grothmann, 2005) observed that with regard to future temperature development, all seven scenarios analysed by scientists exhibit a definite warming trend. The range of warming of the long-term annual average temperatures up to the year 2080 was +1.6 to +3.8 °C. Some scenarios show a particularly strong warming in the southwest of Germany. All seven scenarios show an increase in winter precipitation, while most scenarios show a decrease in summer precipitation. In their model, an especially pronounced increase in winter precipitation was projected for southern Germany, where agriculture and forestry are considered to be highly vulnerable to rapid warming. Moreover, other studies in Germany have concluded that the climate change impacts on forestry especially regarding an increased risk of diseases and pests, forest fires and other extreme events are also significant (Schröter et al., 2005), (ForstBW, 2014b), (ForstBW, 2011).

1.1.2.4 Climate change induced extreme events

Due to global climate change, it is believed that the risk of further and stronger storms is increasing (Jiao-jun, Zu-gen, Xiu-fen, Matsuzaki, & Gonda, 2004). (Banholzer, Kossin, & Donner, 2014) assess the potential impact of changing climate on hazards and extreme events. Their observational data which has been collected since 1950, indicates increases of extreme weather events. The recent Special Report on Extreme Events and Disasters (SREX) by the IPCC predicts further increases in the twenty-first century, including a growing frequency of heat waves, rising wind speed of tropical cyclones, and increasing intensity of droughts (Murray & Ebi, 2012).

Increases in disaster risk and the occurrence of disasters have been evident over the last five decades (MunichRe, 2015). This trend may continue and may be enhanced in the future as a result of projected climate change, further demographic and socio-economic changes, and trends in governance, unless concerted actions are enacted to reduce vulnerability and to adapt to climate change, including interventions to address disaster risks (IPCC, 2012, p. 70). The IPCC confirms that climate change, whether driven by natural or human force, can lead to changes in the likelihood of the occurrence or strength of extreme weather and climate events such as extreme precipitation events or warm spells (Seneviratne et al., 2012). (Foelsche, 2005) also describes the theoretical background and observational evidence of extreme weather events through climate change.

1.1.2.5 Forest vulnerability to climate change and extreme events

Climate change is one of the most important challenges in forestry (Kirilenko & Sedjo, 2007), because it alters the forest growth, due to less or excess precipitation and temperature variations. Trees are durable and static, and forests are exposed to very different environmental and growth conditions throughout their life span. If the forests failed to adjust to environmental changes, the individual tree would weaken, and the entire forest ecosystem would be disturbed. Climate change might expose the trees that are well adapted to the current climatic condition at their location to increasing problems (BMEL, 2014). For example, higher temperatures promote the proliferation of harmful insects such as oak and pine processionary moths. These pests kill the trees and are in some cases, a serious health risk (AGDW, 2014). A changing climate increases the probability of shifts in forest biomass, as tree species are subject to increasing temperatures and/or changes in water regimes (M Hanewinkel, Peltola, Soares, & González-Olabarria, 2010).

For 30 years, a systematic scientific sampling of data regarding forest damage and soil condition - due to climate and weather related disturbances - has been carried out throughout the Federal Republic of Germany. Effects on the potential distribution of (tree) species and, thus, on the future impacts are summarized in climate change literature (M Hanewinkel et al., 2010). The vulnerability of the forestry sector in Germany, to climate change as well as adaptations to these impacts are discussed in (Schröter et al., 2005), (Chmielewski, 2007). They concluded that the Norway Spruce is particularly impacted by climate change – due to calamities, e.g., bark beetles and damages through extreme events such as winter storms.

In Baden-Württemberg, climate and weather related disturbances and damages are also systematically assessed and recorded (ForstBW, 2011, 2014b). Climate change in relation to Baden-Württemberg is portrayed by a report of (MUKEBW & LUBW, 2012). The report acknowledges the climate change related studies by World Meteorological Organization (WMO) and IPCC and restates the increasing and clear trend of global climate change. Furthermore, by showing the outcomes of different state government funded research projects such as KLIWA (*Klimaveränderung und Konsequenzen für die Wasserwirtschaft)* or KLARA (*Klimawandel – Auswirkungen, Risiken, Anpassung*), the report confirms that Baden-Württemberg is also notably affected by climate change. (ForstBW, 2011) also confirms the weather and climate related change in the forests in Baden-Württemberg and indicates that since 2001, defoliation has considerably increased.

Therefore, climate change and climate change induced extreme events such as winter storms put the forest resources and forest management of Baden-Württemberg in an extremely vulnerable position (Figure 1.10).

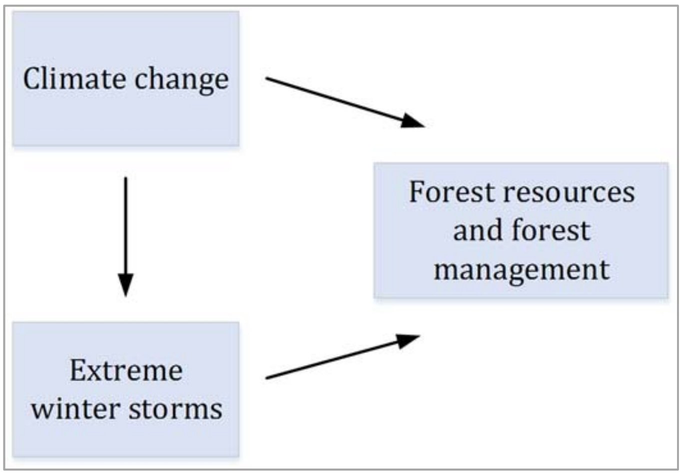

Figure 1.10: Impact of climate change and extreme winter storms on forests

There is a growing concern that changing climatic conditions, and their effects on forests, in the longer term, may result in forests turning from being a net sink of carbon to a net source of carbon. This highlights the need for adapting forests and forest management to expected changing climate conditions (ForestEurope, 2015). Therefore, climate change related adaptation strategies are proposed at different scales (IPCC, 2012; MUKEBW, 2014; StadtKarlsruhe, 2013; Unseld, 2013). (Kolström et al., 2011) present a comprehensive review of potential adaptation options for forestry in Europe based on three pillars: a review of the scientific literature, an analysis of current national response strategies, and an expert assessment based on a database compiled in the ECHOES (Expected Climate Change and Options for European Silviculture) project within COST (European Cooperation in Science and Technology) Action FP0703[17].

1.1.3 Motivation of the research

The motivation of this research is to assess the vulnerabilities of forest resources due to extreme winter storms and to analyse associated economic impacts. Both tasks are complex to assess. The probability and spatial distribution of extreme

[17] http://www.cost.eu/COST_Actions/fps/FP0703.

winter storms changes from time to time and it is not yet possible to quantify the change and to exactly assess the potential economic damage (Schafferl & Ritz, 2005). The assessment of regional and sectoral effects is ambiguous as the effects are region specific and sometimes uncertain. With better data, the assessment of impact in one particular sector due to a certain event is more realistic. (Schafferl & Ritz, 2005) highlighted the need of a new research field to analyse the extreme events and their consequences. (K. L. Abt, Huggett Jr, & Holmes, 2008) emphasized that economic assessment should be sensitive to the spatial scale (geographic area to be assessed), temporal scale (time span used to assess impacts), and sectoral scale (economic sectors included).

Therefore, an interdisciplinary research - focusing on Geographic Information Systems (GIS) based statistical modelling, forest economics and management practices, as well as system dynamics modelling approach - has been applied to analyse the impacts of extreme winter storms on the forests in the state of Baden-Württemberg (Figure 1.11). The overall modelling framework and the results can help public and private forest owners to understand whether their forests are vulnerable or at risk to extreme winter storms and if so, what the possible impacts would be, especially regarding the decisions on salvage[18] operation and forest management. In this way, it will assist them to prioritize decisions, prepare future actions and to improve the understanding in the events of extreme storms.

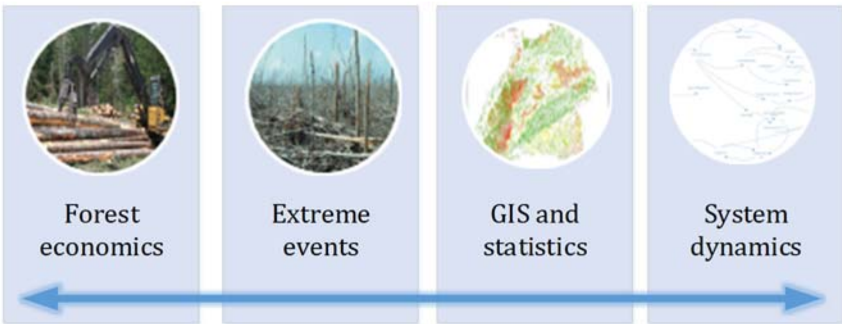

Figure 1.11: Scope of interdisciplinary research covering forest economics, extreme events, GIS, statistics and system dynamics

Furthermore, a decision support tool that can address the spatial and temporal aspects of forest management and salvage operations both for short and long term is required. The complicated interactions among factors affecting the vulnerability of tree stands to wind damage are known. But is not yet possible to determine,

[18] Salvage includes the wood logs from the broken and windthrown trees (more explanation is given in Figure 3.1).

purely based on experimental studies, how the risk changes over time as it is affected by forest dynamics, management and environmental conditions (M. Hanewinkel, Hummel, & Albrecht, 2011). Such a decision support system is not yet implemented in the theoretical literature or in practice but is extremely useful to foresters.

The proposed system dynamics modelling approach should be viewed as a decision support system that aids foresters concerning the forest management and salvage operation decisions immediately after an extreme winter storm. It is meant to ask 'what-if' questions for alternative decisions and represents an important tool to evaluate these decisions, e.g., concerning determination of salvage price, salvage value, costs associated with salvage operation, forest clearing areas[19] (*Kahlflächen*), etc.

Therefore, the motivation of this research is predominantly to answer following **primary questions**:

- What are the most important factors that influence the vulnerability of forests?
- Where are the forests in Baden-Württemberg most vulnerable to extreme winter storms and to what degree?
- What are the essential variables that help to assess the economic impacts of extreme winter storms on forestry?
- How do extreme winter storms affect the forest resources and forest management and what would be the possible economic impacts?
- How do alternative forest management and salvage operation strategies influence the overall economic impacts?

1.1.4 Literature review and research gap

Regarding modelling storm damage, (M. Hanewinkel et al., 2011) carried out a detailed overview of different methodological approaches. Most of the studies work on a regionally limited spatial level and only cover one major damaging event, e.g., a storm or catastrophic snow breakage.

Some expert systems were designed, e.g., (Rottmann, 1986) developed an expert system of storm damage to forests in Germany. (Mitchell, 1998) developed a diagnostic framework for windthrow risk estimation in Canada which is similar to

[19] Forest clearing areas are storm affected areas where trees are damaged and reforestation is needed.

an expert system. (Kamimura, Gardiner, Kato, Hiroshima, & Shiraishi, 2008) also developed a decision support approach to reduce wind damage risk. The inclusion of risk and vulnerabilities into the economic analysis of forest management has a long tradition (M. Hanewinkel et al., 2011). In the classical Faustmann approach to represent the change in the value of forest areas, the timber prices and costs, timber yields, etc. are assumed constant over the forest rotation (Navarro, 2003), (Tahvonen & Viitala, 2007). But due to extreme events such as winter storms, timber prices and costs, etc. are subject to various risks and uncertainty, which might result in periodical fluctuation of their values.

Similarly, the assumption made that the interest rate is known and constant over the period may not be valid. Thus forest investments take place in an environment of risk and uncertainty (M. Hanewinkel et al., 2011). (Schwarzbauer, 2007) investigated the influence of salvage cutting on timber prices. (Reed, 1984) showed the importance of the consideration of a discount rate in such risk. Recently, (Brunette, Couture, & Laye, 2015) analysed the impact of storms on forest owners' harvesting decision through a Markov decision process modelling framework. (Riguelle, Hébert, & Jourez, 2015) considered regional forest-wood chain dynamics after a hypothetical storm event and developed a decision support system that compares changes in the dynamics of the regional forest-based sector (e.g., sales, harvesting, transport and transformation) under various crisis management options. But no damage assessment, which is very important for the post-storm strategy, was performed.

The impacts of different extreme events and disturbances in forestry were also studied based on empirical and statistical based models. For example, (K. L. Abt et al., 2008) reviewed the modelling requirements and then designed an economic impact assessment for US wildfire programmes. (Prestemon & Holmes, 2008) developed a model that describes the potential market impacts due to fire damaged salvage timber in southwest Oregon, USA. (Pascual & Guichard, 2005) used cellular automata method[20] to model fire and wind damage to forests. (Holthausen, 2006) discussed some case studies on different economic aspects, e.g., economic losses due to storm damage, windthrow management and risk management with an emphasis on insurance solutions. In this regard, the storm Lothar in Switzerland was considered as an empirical case study.

[20] A cellular automaton (CA) is a collection of cells arranged in a grid, such that each cell changes state as a function of time according to a defined set of rules that includes the states of neighbouring cells (Nayak, Patra, & Mahapatra, 2014).

(Hölscher, 2005) examined the impact of disturbances on the interconnectedness of regional standing timber markets in Germany. The disturbances had a longer term effect on the investigated raw wood market, and the impacts varied in the subsequent years and in different federal states. However, immediate elasticities of raw wood price against disturbances were not specified.

Although different approaches to analyse the impacts of different extreme events and disturbances in forestry contingent on empirical and statistical methods exist and some decision support systems were developed, many **research gaps** are identified:

- Most of the studies considered regionally limited spatial extent.
- Most of the studies were performed after the storms had happened, some of them did not consider the periodic fluctuations/dynamics of timber and other input prices, timber yield, etc. before and after the winter storms.
- They did not perform a simultaneous analysis of the vulnerability of forests (i.e., damage assessment) and corresponding economic impacts.
- They did not consider a combined spatial and system dynamic modelling as a decision support system.
- Many studies considered a particular aspect, e.g., timber or salvage. Other factors, e.g., consideration of regeneration of new species in the storm damaged areas, etc. were not considered.

The proposed approach - incorporating GIS, system dynamics and economic aspects to analyse the impacts of extreme winter storms was not carried out in any scale before. Partial studies, e.g., simulation of forest management and handling of machineries in harvesting methods (McDonagh, 2002), (Visser, McDonagh, Meller, & McDonald, 2004), forest growth and pollution (Bossel, 1986), modelling of dead wood (Jakoby, 2005) were performed. In other fields of study, the modelling of GIS and different simulation methods was carried out either separately or coupled loosely. Further literature review on related applications and associated challenges is given in Section 4.3.3.

Therefore, considering the limitations associated with the state of research and overall motivations of this study, the main **methodological objectives** of this research are to:

- Assess the vulnerability of forest resources due to an extreme winter storm in Baden-Württemberg.

- Illustrate the dynamic interactions related to forest economy and forest management and to explain how impacts of extreme winter storms on forests evolve.
- Develop a combined spatial and system dynamics simulation modelling framework to assess the impact of an extreme winter storm in all districts in Baden-Württemberg.
- Perform policy based scenario analyses to evaluate the possible outcome of different forest management and salvage operation strategies.
- Create a decision support system to help decision makers to understand and evaluate forest management options and the potential outcome of salvage operations decisions.

1.2 Methodological approach

1.2.1 Definition of model, method and simulation

A **model** is a simplified representation of a system at a particular point in time or space intended to promote understanding of the real system (Bellinger, 2004). A **system** is a whole that is defined by its function(s) in one or more containing systems (Ackoff & Gharajedaghi, 1996). A system exists and operates in time and space (Bellinger, 2004). Some common characteristics or elements of a system are structure, boundary, behaviour, interconnectivity, sub-systems, etc. Systems can be classified in many ways, e.g., physical or abstract systems, open or closed systems, computer-based systems, real-time systems, etc. Some examples of systems are urban systems, climate systems, economic systems or forest systems.

Some systems are complex in nature. (Anderson, Arrow, & Pines, 1988) define that a complex system is literally one in which there are multiple interactions between many different components. The core sets of features that characterize a complex system are non-linearity, feedback, spontaneous order, robustness and lack of central control and hierarchical organisation (Kremers, 2013; Ladyman, Lambert, & Wiesner, 2013). Forestry is considered as an adaptive complex system. (Filotas et al., 2014; Messier & Puettmann, 2011) showed why forestry is a complex system and provided concrete examples of how to manage and model forests as complex adaptive systems.

Simulation is defined as the manipulation of a model in such a way that it operates in time or space, thus enabling one to perceive the interactions that would not otherwise be apparent because of their separation in time or space (Bellinger, 2004).

In simulation modelling, **method** means a general framework for mapping a real world system to its model (Borshchev, 2013). Three simulation methods exist:

a. System dynamics modelling
b. Discrete event modelling
c. Agent based modelling

Comparative reviews on these models, some applications and possible aggregations were given by (Wakeland, Gallaher, Macovsky, & Aktipis, 2004), (Schieritz & Milling, 2003), (Martin & Schlüter, 2015). The choice of a particular method should be based on the system being modelled and the purpose of modelling (Borshchev, 2013).

The relationship among system, model, simulation and method is illustrated in Figure 1.12.

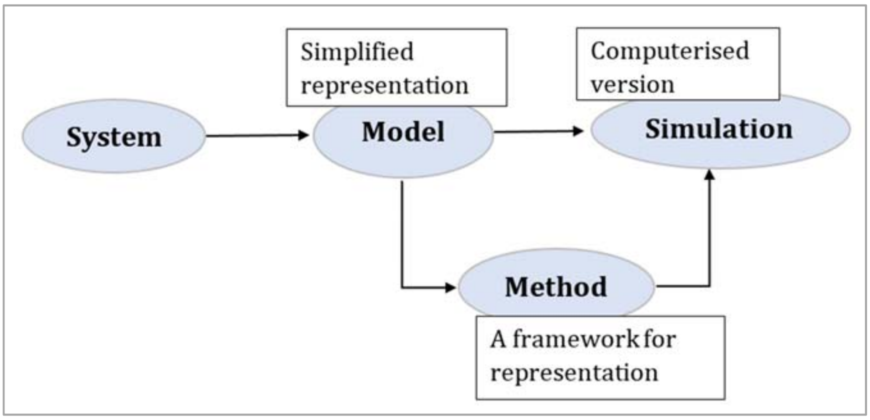

Figure 1.12: Definition and relationships of system, model, simulation and methods

1.2.2 System dynamics model

System dynamics is a computer modelling method used to analyse complex non-linear dynamic feedback systems for the purpose of generating insight and designing policies that will improve system performance (Radzicki, 2011). It was introduced in the mid-1950s by the MIT professor Jay Forrester whose idea was to use the law of physics to describe and investigate the dynamics of economic and social systems (Borshchev, 2013). Such modelling capabilities have proved useful in supporting policy decisions in industrial, social, economic and scientific systems (F. A. Ford, 1999; J. W. Forrester, 1961, 1969, 1972; Sterman, 2000).

The system dynamics model can be described as an iterative, continual process of formulating hypothesis, testing and revision (Sterman, 2000). Five major steps along with multiple sub-steps are involved in designing and implementing a system dynamics model. They require continued inspection throughout the model development process. The main steps are:

a. Problem articulation
b. Formulation of dynamic hypothesis
c. Development of preliminary model
d. Validation and model testing
e. Policy based scenario analysis

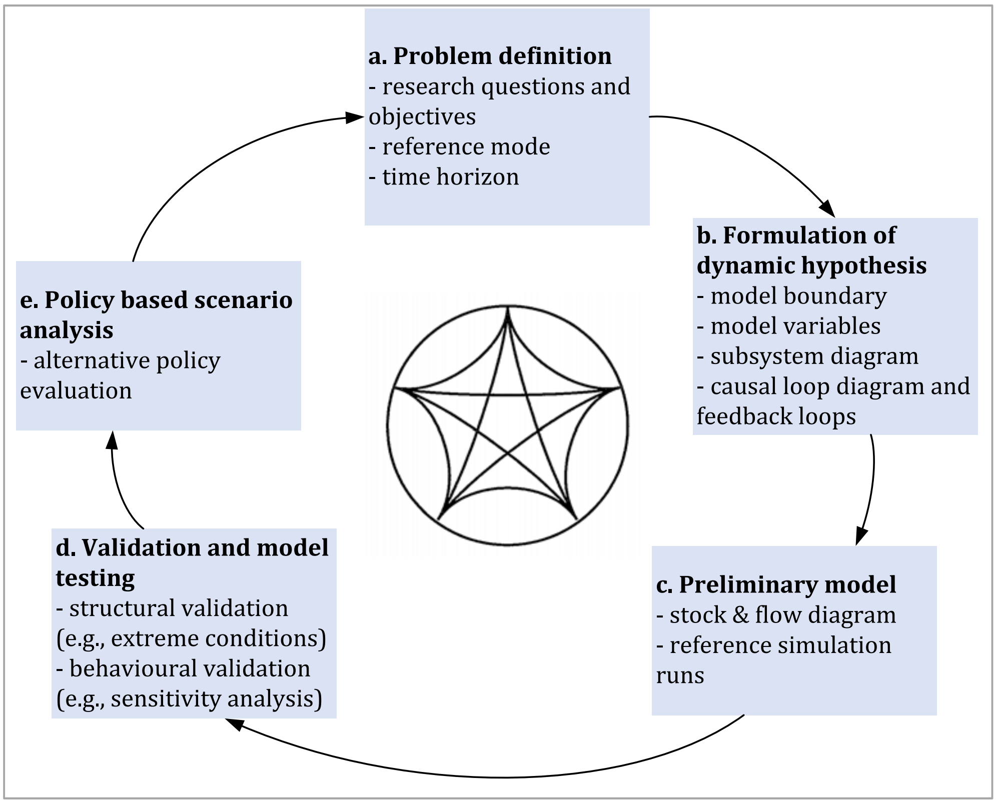

Figure 1.13: System dynamics modelling steps applied in this research[21]

1.2.3 Geographic information systems

Geographic information systems (GIS) were initially developed as tools for the storage, retrieval and display of geographic information (Rogerson & Fotheringham,

[21] Modified after (Sterman, 2000).

1994). They were applied in simple mapping operations and digitization of paper based maps, but today the capabilities and areas of applications have tremendously evolved to rigorous spatial and statistical analysis, manipulation, management and visualization of data. They are attached to many operations and have many applications related to engineering, planning, management, transport, insurance, telecommunications, and business (Maliene, Grigonis, Palevičius, & Griffiths, 2011). GIS are generally used for some level of decision support, e.g., mapping of environmental risk and vulnerability, natural resource management, evaluation of policies, etc. (Thomas & Sappington, 2009), (Nyerges & Jankowski, 2009).

1.2.4 Weight of evidence

Weight of evidence (WofE) is a data driven method which uses Bayesian statistics to calculate posterior probability of an event or occurrence (Agterberg, Bonham-Carter, Cheng, & Wright, 1993). In this regard, the prior probability is updated by quantifying the spatial association between evidence themes[22] (e.g., forest type, wind speed, soil type, etc.) and training data set (e.g., windthrow occurrence).

The significance of these evidence themes is tested through formulation of multiple models in order to understand the important variables influencing the development of WofE modelling. Finally, the most significant model is considered to create the posterior probability maps, e.g., to predict the windthrow vulnerability.

1.2.5 Formulation of research methodology

The spatial modelling of forest vulnerability and storm damage is performed by GIS. But the temporal aspect, especially the dynamics of modelling is not yet suitably addressed by GIS. Dynamic models provide insights into the process inherent in the evolution of a system, whereas GIS provide spatial databases and allow for spatial and statistical analysis, interpretation and visualization of data (Bahu, Koch, Kremers, & Murshed, 2013). On the other hand, the strength of many simulation methods, e.g., system dynamics lies in representing temporal processes. Moreover, the economic theories of any particular sector under investigation can be incorporated into system dynamics models but such models do not adequately represent spatial processes.

[22] They are basically different environmental variables, each of them can have different number of classes. For example, forest type evidence theme consists of three classes, e.g., coniferous, deciduous and mixed. Further explanation is given in Section 3.3.3.2.

Therefore, the combination of GIS and system dynamics will enable development of a model that is both dynamically and spatially explicit and holds enormous advantages for economic modelling and decision making. Such a combined spatial and system dynamics modelling approach provides decision makers with the capability of capturing spatially referenced feedback processes in dynamic systems and to display their temporally varying characteristics on maps. This modelling capability in time and space could be applied in different fields of research, e.g., assessment of economic impact due to extreme events, management of natural resources, modelling of an ecosystem, evaluation of climate change impact or support in management, operation decision making, etc. (see Section 4.3.3).

Two models are, therefore, developed for this purpose (Figure 1.14). The first model is based on the statistical method Weight of Evidence and GIS to analyse the vulnerability of forest resources (trees) due to a stochastic extreme winter storm[23] for all the districts in the state of Baden-Württemberg in Germany. For this reason, the effect of wind on trees and the influences of spatially relevant environmental parameters are studied. The outcome of the WofE model is integrated into the system dynamics model where dynamics related to forest economics, forest management and salvage operation decisions are also incorporated to assess and evaluate the impacts due to that particular storm. The final model is able to show the changes in impacts over time (i.e., years) and space (i.e., districts) as the model components are constantly evolving as a result of previous feedback actions.

[23] The winter storm model is based on (Hofherr & Kunz, 2010). Spatially highly resolved wind fields of severe historical storm events over Germany during the climatological period between 1971 and 2000 are modelled by a statistical - dynamical downscaling approach with the Karlsruhe Atmospheric Mesoscale Model KAMM (see Appendix 2).

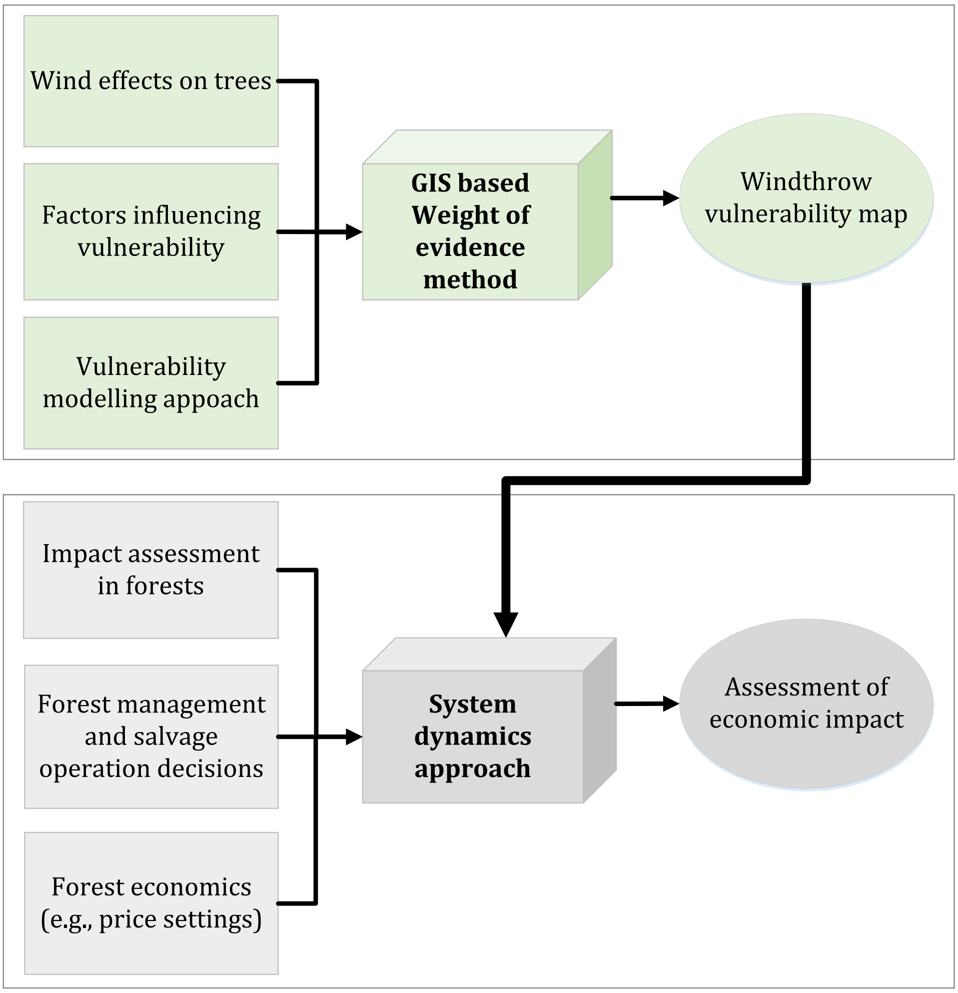

Figure 1.14: Overall methodological approach to assess the impacts of extreme winter storms on the forest resources

1.3 Outline of the thesis

Chapter 1 explains the concept and motivation of the research with a clear description of the problems associated with extreme winter storms in the forests in Baden-Württemberg. Then the methodological approach is elaborated with a definition of key terms associated with the formulation of research and an overview of the state of research. Finally, an overview of the thesis structure along with a short description of each chapter is given.

In **Chapter 2**, forest resources and related management practices are described. In Section 2.1, a description of the socio-economic structure of the state of Baden-Württemberg is given. Then a statistical overview of the forest resources, use and flow of wood resources are given in Section 2.2. Finally, the forest management related laws and regulation, best practices before and after extreme storms, as well as various statistical data and assumptions required for modelling economic impacts are described in Section 2.3.

The vulnerability of forest resources due to extreme winter storms is analysed in **Chapter 3**. At first, the effects of wind on trees and associated phenomena are described. A comprehensive literature review on assessment of storm damage, determining factors of windthrow, as well as several modelling approaches, (e.g., deterministic and empirical models) and their characteristics, advantages, limitation, applications are discussed. In Section 3.3, the empirical WofE model is introduced with a definition and identification of the modelling approach. Different steps associated with windthow vulnerability assessment are then systematically described and multiple model outcomes are evaluated and validated in order to justify the acceptance of the final posterior probability map of the vulnerable forest areas in Baden-Württemberg.

Chapter 4 describes the theories associated with modelling of economic impacts and system dynamics. In Section 4.1, a literature review on impact analysis and research challenges regarding impact analysis in forestry are described. For such impact assessment, understanding of economics of salvage decision, timber and salvage market reactions after the storm, as well as salvage operation modelling aspects are important to identify. They are described in Section 4.2. Finally, the components of system dynamics and its integration into the economic modelling and GIS are described with different applications and associated challenges.

In **Chapter 5**, the economic impacts of extreme winter storms on forestry are analysed using the combined spatial and system dynamic approach. For this reason, the system dynamics modelling approach and related assumptions are explained. Thus the forestry sector is divided into five submodels. In Section 5.2, the dynamics of the model parameters and the associated assumptions of these submodels are illustrated. The data sources for the reference simulation run and corresponding results of all the submodels are explained and evaluated in Section 5.3. Then the system dynamics model structure and results are validated through a set of structural and behavioural tests.

In **Chapter 6**, firstly two policy based scenarios, e.g., immediate salvage operation and delayed salvage operation, are performed to evaluate the possible economic impacts due to alternative salvage operation practices. Then in Section 6.2, sensitivity analysis of some of the critical input parameters to the endogenous parameters and to overall model results are tested by increasing and decreasing certain parameters.

Chapter 7 summarizes the thesis and gives further insights into the limitation of the approaches, as well as some open research questions. To conclude, a research outlook is given in Section 7.3.

Finally, these seven chapters are complemented by six **appendices**. Appendix 1 and Appendix 2 describe the WofE modelling tool and the characteristics of required dataset to analyse the vulnerability of forest resources. Then the results of the statistical analysis of different evidence themes and multiple WofE model runs are illustrated in Appendix 3 and Appendix 4, respectively. Appendix 5 summarizes various parameters and variables used in the five system dynamics submodels to assess the economic impacts of extreme winter storms on forestry. Finally, the graphical user interface of the decision support tool is illustrated in Appendix 6.

The general structure of the thesis as well as the dependencies of different chapters and sub-chapters are illustrated in Figure 1.15.

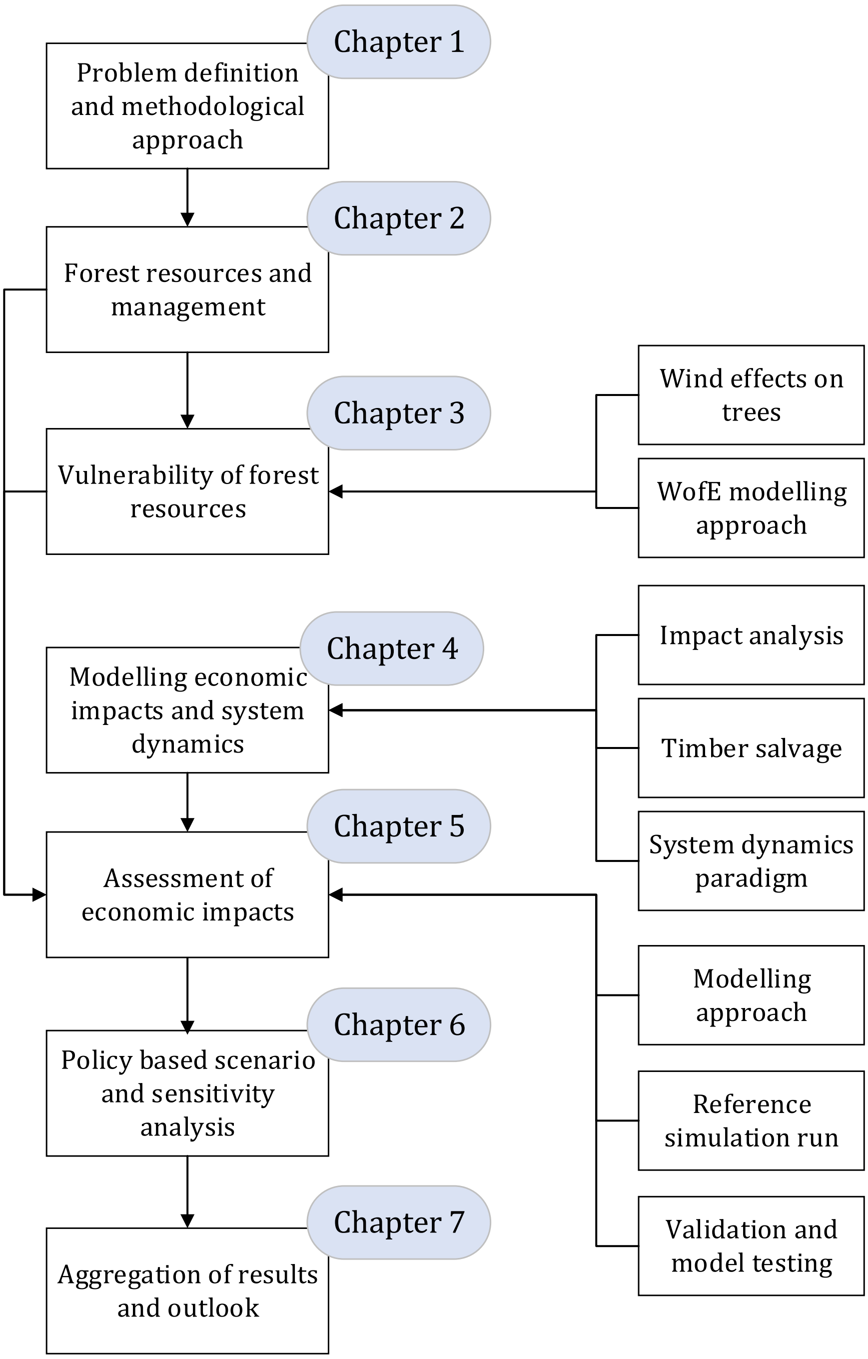

Figure 1.15: General structure and content of the thesis

2 Forest Resources and Management in Baden-Württemberg

2.1 Description of Baden-Württemberg

2.1.1 Administration and geography

Baden-Württemberg is one of the 16 federal states in the Federal Republic of Germany. It is the third largest state in terms of size and population, with an area of 35,751 km^2 and 10.63 million inhabitants (StaLaBW, 2014). Baden-Württemberg shares borders with France, Switzerland and the states of Rhineland-Palatinate, Hessen and Bavaria. It is broken down into 35 rural districts (*Landkreise*), 9 urban districts (*Stadtkreise*) and 1,101 municipalities (*Gemeinden*), which form the lower administrative tier. In terms of size, only nine municipalities have a population of more than 100,000 inhabitants (STMBW, 2015). The state capital is Stuttgart. Figure 2.1 illustrates the administrative boundaries and population density of the urban and rural districts in Baden-Württemberg.

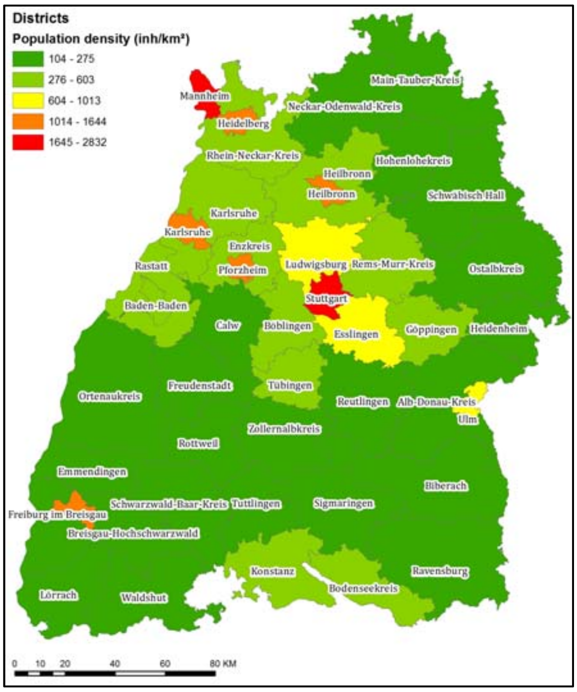

Figure 2.1: Population density of the districts in the state of Baden-Württemberg

2.1.2 Economy

Within Europe and Germany, Baden-Württemberg has one of the strongest economies with a GDP of 389.4 billion Euros in 2012 and enjoys one of the highest standards of living. It has one of Europe's, as well as Germany's lowest rates of unemployment. As of February 2015, the unemployment rate was 4.1% (StaLaBW, 2015a).

Baden-Württemberg is home to many of the world's market leaders. The technological diversity is particularly visible in the wide range of industrial sectors. The Cluster Portal in Baden-Württemberg identified 25 technology sectors[1], of which mechanical and automotive engineering, electrical engineering, information technology, energy, forest and wood-based industry are the key sectors.

The forest and wood-based industry is one of the strongest economic sectors in the Federal Republic of Germany in terms of revenue and employment. This applies in particular to Baden-Württemberg, where 29,000 wood-based companies employ 175,000 people and generate an annual turnover of 31 billion Euros (Clusterportal-BW, 2015). This high degree of diversification and specialization of forest and wood industry contributes about 7% to the state's GDP (in comparison to 2% on an all-Germany level) (FVA 2005).

Moreover, the region's economic development depends to a large extent on the performance and competitiveness of small and medium-sized enterprises (SMEs) (EURES 2015). Two thirds of all employees work for SMEs. In compliance with the national average, the largest section of the forest and wood-based industry of Baden-Württemberg is characterized by small and medium-sized businesses which are mostly based in rural areas. Worldwide leading manufacturers of the wood processing industry, notably producers of woodworking machinery, paper machines and tool systems are located here. Baden-Württemberg is also market leader in the field of pre-fabricated timber construction. Many other industrial sectors, e.g., mechanical engineering, tool construction or the metal industry, logistics, the packaging industry and the energy sector are dependent on these forest and wood-based industries.

[1] http://www.clusterportal-bw.de/en/technology-fields

2.2 Forest resources

2.2.1 Basic statistics

2.2.1.1 Federal Republic of Germany

The Federal Republic of Germany is one of the most densely wooded countries in Europe. About one-third of the national territory (11.4 million ha) is covered with forests (BMEL, 2014). Forest territories increased in size by about one million ha in Germany over the past four decades. During the second and third National Forest Inventories (NFI)[2], i.e., 2002 and 2012, the forest areas have changed very little. Against a loss of 58,000 ha, about 108,000 ha new forest areas were gained – with a net growth of 0.4% during this period (BMEL, 2014).

About 48% of the forest is private, 29% belong to the states, 19% is community forest and 4% belongs to the Federal Republic of Germany (BMEL, 2014). Coniferous trees[3] are mostly dominant in Germany. But between 2002 and 2012, the areas for deciduous trees[4] have increased while coniferous trees have reduced (BMEL, 2014). For example, areas for Norway Spruce (*Picea abies*, German name *Fichte*) have reduced to 8% (242,000 ha) while European Beech (*Fagus sylvatica*, German name *Buchen*) areas have increased by 6% (102,000 ha).

2.2.1.2 Federal State of Baden-Württemberg

Baden-Württemberg has the second richest reserves of wood (after Bavaria, in terms of area) in Germany (Figure 2.2). According to the recently published third NFI, the forest areas in Baden-Württemberg have slightly increased from 1,359,928 ha (1987) to 1,362,229 ha (2002) and finally to 1,371,886 ha in 2012 (Kändler & Cullmann, 2014).

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[2] https://www.bundeswaldinventur.de

[3] Trees with small, waxy and narrow leaves, e.g., Spruce, Fir, etc.

[4] Trees those drop leaves each autumn, e.g., Oak, Poplar, Beech, etc.

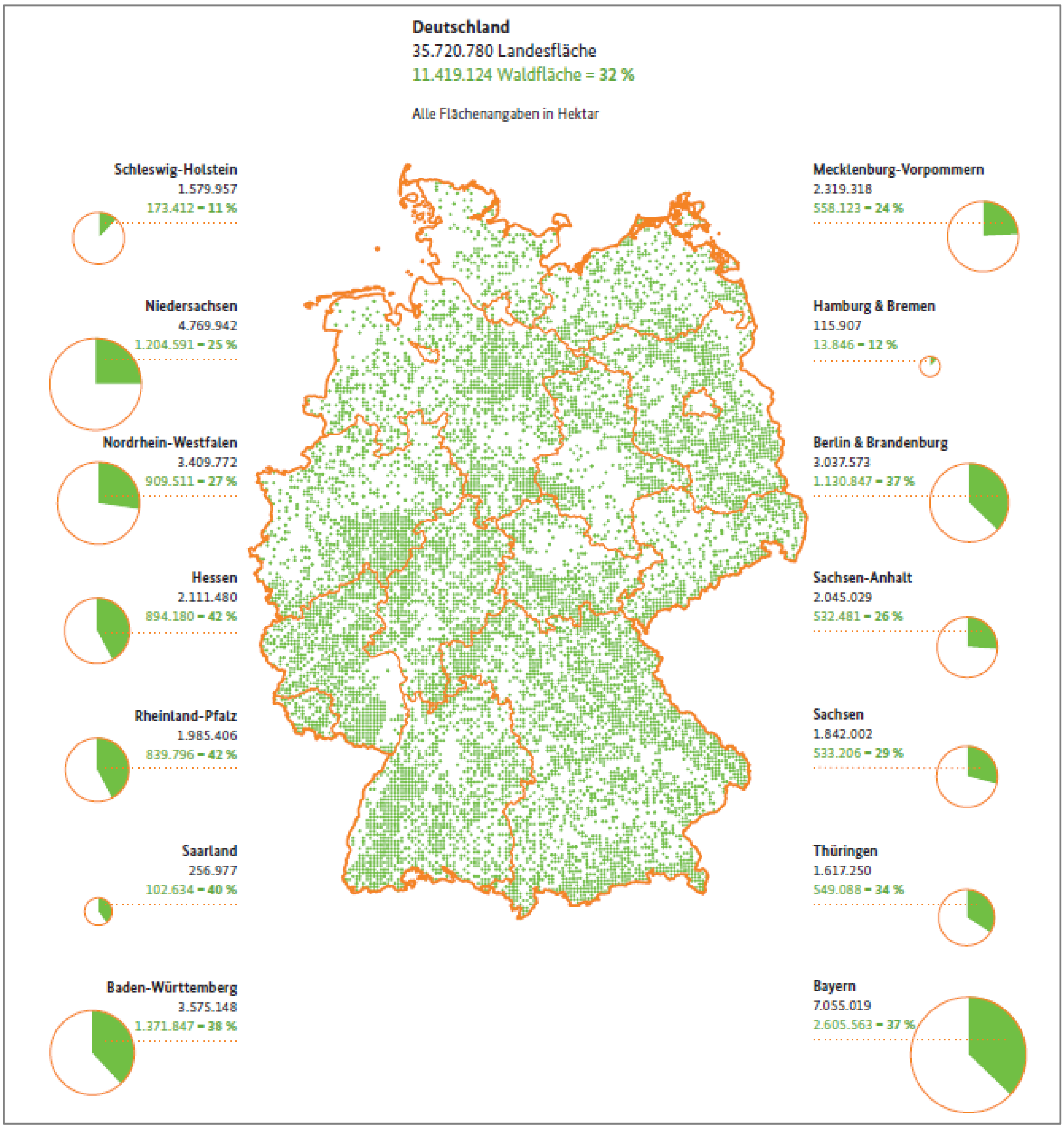

Figure 2.2: Distribution of forests in Germany[5]

The ownership patterns of forests have not changed in the last 25 years. 40% of forest areas belongs to corporate forests owners, 35.9% to private foresters, 23.6% to state forests and the remaining 0.5% belongs to Federal Republic of Germany.

About 50 different types of tree species are available in the forests in Baden-Württemberg. Spruce (*Fichte*), Beech (*Buche*), Fir (*Tanne*), Pine (*Kiefer*), Oak (*Eiche*) occupy three-fourths of the forest area. Other important species are Ash (*Eschen*), Sycamore Maple (*Bergahorn*), Douglas Fir (*Douglasie*), Larch (*Lärche*), Hornbeam

[5] (BMEL, 2014).

(*Hainbuche*), Birch (*Birken*) and Alder (*Erlen*). The share of some important species in the forests in Baden-Württemberg is shown in (Figure 2.3).

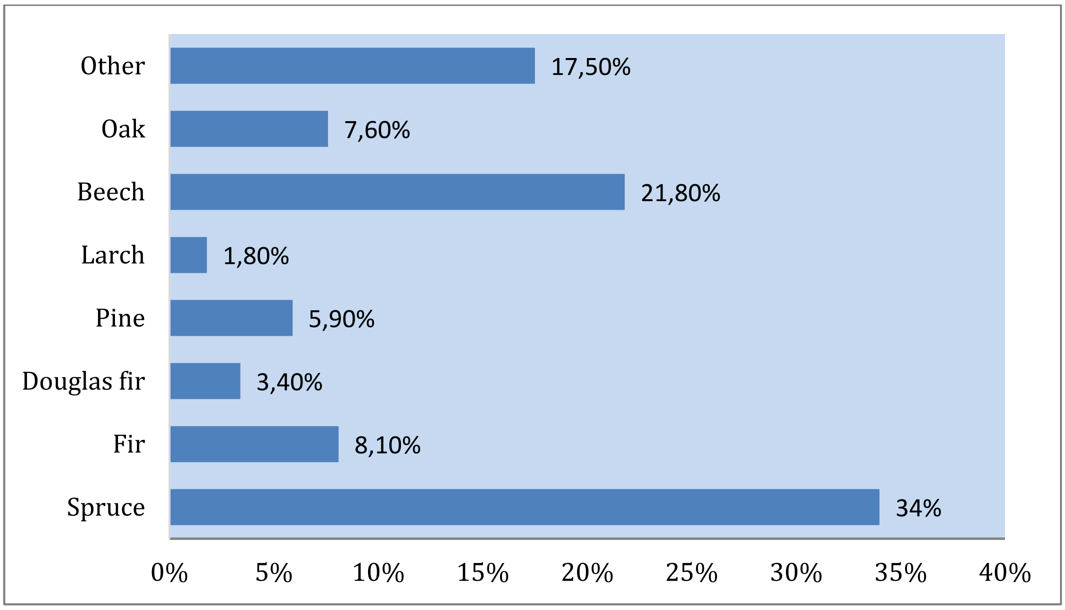

Figure 2.3: The share of important tree species in the forests in Baden-Württemberg

Since 1987, the proportion of deciduous trees (e.g., Beech) has increased continuously from 36.1% in 1987 to over 42.9% in 2002 and up to 46.8% in 2012. On the contrary, the share of coniferous trees (e.g., Spruce) has decreased gradually (Figure 2.4).

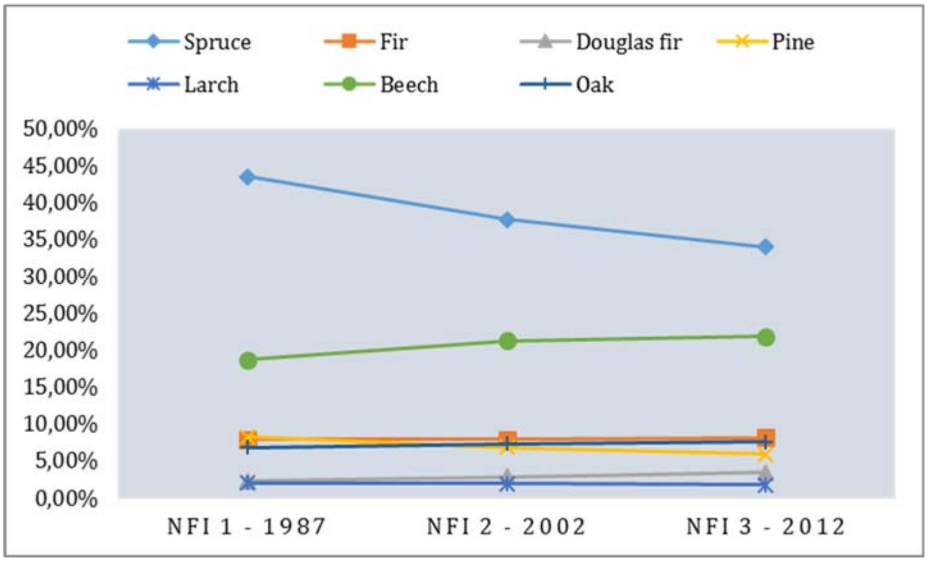

Figure 2.4: Historic development of important tree species in Baden-Württemberg

2.2.2 Wood use and flow

Forestry is very important to the state of Baden-Württemberg as it supplies wood resources for material and energetic use and plays a central role in energy transition, climate protection, etc. Three main types of wood, e.g., round wood, industry wood and wood residues are extracted from forest trees (Figure 2.5).

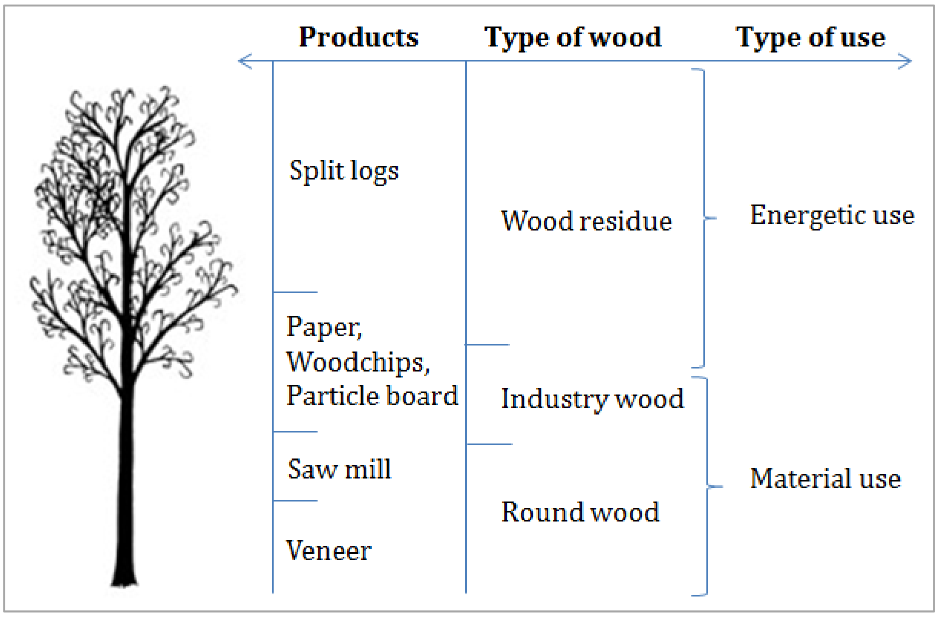

Figure 2.5: Tree parts and their use as a material or an energetic source

They are transported to different industries to prepare diverse products and finally used either as a material or an energetic source. For example, wood residue is used for energy generation, industry wood is used in paper or particle industries and the round wood is transformed to sawmills and veneer industries for material use. Several by-products are also produced, e.g., sawmill by-products, industry wood residues, bark, recovered/old wood and landscaping wood.

Baden-Württemberg is mostly occupied (approximately 60%) by Norway Spruce and European Beech (Figure 2.3). Regarding their share in forest products, Spruce is mostly used in sawmills (80%) and paper and pulp industries whereas Beech is mostly used in bioenergy plants (48%) (FVA, 2005).

Wood flow can be defined as the path timber follows from when it is first harvested, to the final product in a consumer's hand. These flows are complex and interconnected, involving a large number of stakeholders and resulting in a large number of final products ranging from paper products, bioenergy fuel, furniture, construction supplies and raw material exports. Once timber leaves the forest, the flow of material can be bi-directional, with a single mill potentially engaged in both the sale and purchase of (bi) products.

The supply and demand for both raw resources and final products have a major influence on the different flows of wood resources in the market. The complexity of the forests both in species composition and in ownership, as well as the number of industries utilizing these resources in Baden-Württemberg, makes wood flows extremely difficult to assess. However, based on the available statistics and related literature, (Becker & Brüchert, 2007) attempted to give an overview of wood flow in the state of Baden-Württemberg.

2.2.3 Wood resource balance

A wood resource balance compares the supply of wood raw material with the material and energy use in a national economy. It is a consistency check of national wood flows that counter-checks the sums of all sources of wood materials against the balance sheet total of the consumption side (Mantau, Steierer, Hetsch, & Prins, 2007). (Mantau, 2005) developed a framework (Figure 2.6) to assess the structure of the wood resource balance in Germany which was also applied in other European countries (Mantau et al., 2007) and validated for the state of Baden-Württemberg.

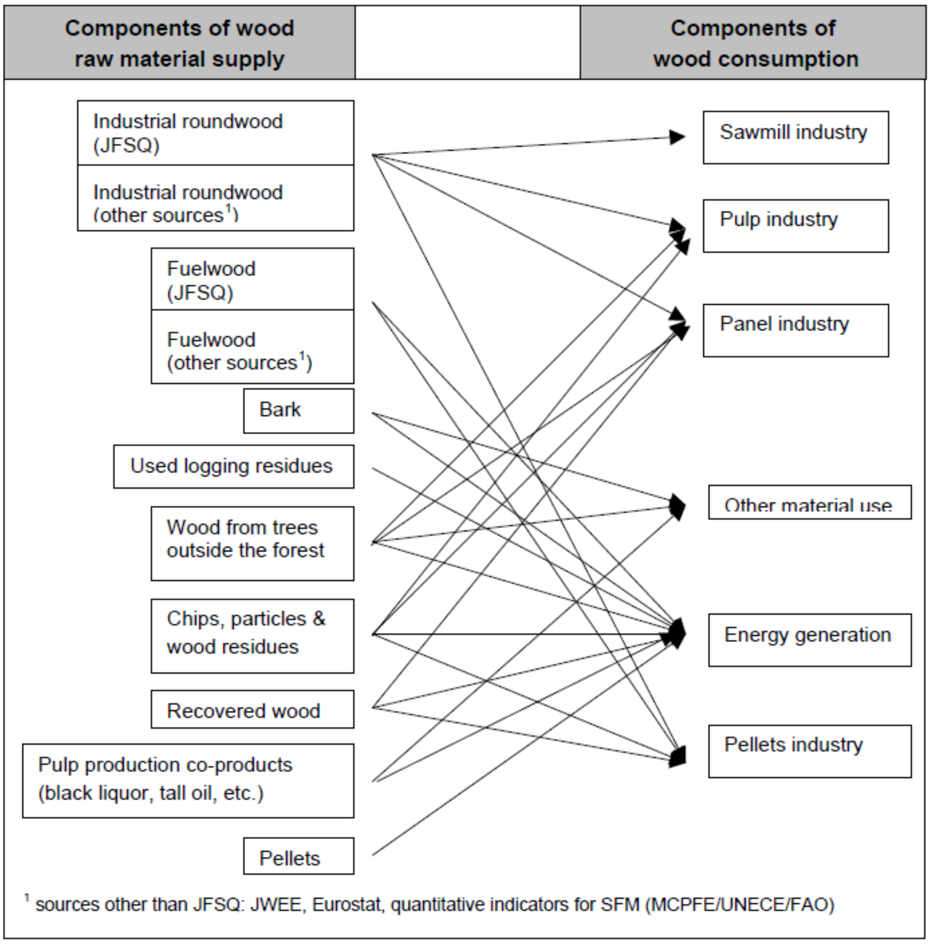

Figure 2.6: Components of wood supply and consumption in the wood resource balance[6]

The raw wood material balance in Germany for the years 2005 and 2010 is investigated by (Mantau, 2005) and (Mantau, 2012). The intake of wood in different forms, e.g., round wood, industry wood, old wood, bark, etc. from the forest and from outside of forests, as well as use of this wood for different purposes, e.g., as material use in sawmills or in wood processing industry and as energy use in biomass plants or in domestic fuel are compared and then balanced. In 2005, about 38% of total available raw wood from forests and other sources in Germany was used for energy purposes and the rest was used for material purposes (Mantau, 2005).

(Mantau, 2012) observed that the total timber supply and consumption in Germany in 2010 was 135 million m^3. About 64% (86 million m^3) of the timber originated directly from the forests, and the rest was produced as sawmill by-product, wood energy by-product, old wood, landscaping conservation material, etc. In Baden-Württemberg, the wood demand is about 10.9 million m^3 per annum (MLR, 2010).

[6] (Mantau et al., 2007).

Considering that about 64% of this demand is met by wood from forests, approximately 7 million m^3 of timber comes from the forests in Baden-Württemberg.

On the other hand, the annual average timber cut in Baden-Württemberg is roughly 8.4 million m^3, varying from 7.5 million m^3 in 2009, to 9.0 million m^3 in 2011, to 8.2 million m^3 in 2014 (StaLaBW, 2015b). About 78% of the total timber sold from the forests in Baden-Württemberg between 2000 and 2009 remained within the state, while 10% was exported to Bavaria, 5% to other countries such as Switzerland and France, 3% to North Rhine-Westphalia and the rest to other federal states (MLR, 2010). Therefore, from the yearly cut, about 6.6 million m^3 (8.4 million m^3 x 78%) of raw timber is made available from the forests in Baden-Württemberg in order to meet the demand of the state. The rest of the demand is met by importing from other states and countries. Unfortunately, statistics on the import and export of timber is not available for Baden-Württemberg, but only for the Federal Republic of Germany. For example, in Germany approximately 8.5 and 3.1 million m^3 of raw wood was imported and exported, respectively in 2014 (BMELV, 2015).

2.3 Forest management

2.3.1 Forest laws and guidelines

The political power in the Federal Republic of Germany is allocated at three different levels, e.g., the municipalities, the 16 federal states and the federation. Many legislatives and most of the executive competences are allocated at the federal state level. The forest related legal framework is generally dominated by the dualism of both the forest law and the nature conservation law. Other laws for the protection of certain aspects of ecosystem management, e.g., soil protection, may interfere with this legal framework (Spielmann et al., 2013).

The Federal Forest Act of Germany (FFA) sets guidelines and framework regulations for German forests. This act, along with the forest laws of the individual states, serves for the benefit and use of forests since 1975. The act regulates improper handling, over-exploitation, depletion and loss of area coverage within the forest (Roering, 2004). The aim of the FFA is to conserve and increase the country’s forests regarding its economic, environmental and recreational functions and to secure their proper management, to advance forestry and to balance the interests of the general public with those of forest owners (FFA §1)[7].

The Forest Act of Baden-Württemberg (FABW) is an obligatory standard set for all the forest owners in Baden-Württemberg. It develops four concepts to guarantee the maintenance of species in forests: the Old and Deadwood concept (AuT), species fact sheets, Natura 2000 management plans and the species protection programme. These concepts complement each other and provide a flexible, comprehensive instrument for the protection of the specific habitat and certain species in forests (Spielmann et al., 2013).

Other relevant acts and guidelines exist on water protection, soil protection, environmental damage, reproductive material, plant protection, forest development types and tending young stands. The detailed description of the FFA, FABW and other related acts are given by (Spielmann et al., 2013), (Roering, 2004) and (Kratsch, Reinöhl, & Rohlf, 2006).

A guideline on the silviculture management for the forests of Baden-Württemberg was prepared by (ForstBW, 2014a). ForstBW, the State Forest Administration of Baden-Württemberg, is the body responsible for the implementation of forest policy and forestry issues in Baden-Württemberg. The forest policy, through norms and legislation, financial means and information as well as forest programmes, aims to promote the sustainable silviculture management and use of forest land resources[8].

Silviculture is the science and art of growing and tending forest crops, based on knowledge of silvics, i.e., the study of the life history and general characteristics of forest trees and stands, with particular reference to locality factors (Robertson & Calder, 1971). The silviculture management aims at providing long-term ecological stability to the tree stands against winter storms or other calamities and for this reason, provision of site-adapted tree species is promoted. The ForstBW provides specific guidelines and concepts for different forest development types (*Waldentwicklungstypen-Richtlinie*), the initial situation (e.g., forest history, site characteristics, ecological situation, etc.), goals in terms of species composition, mixture and structure and silvicultural measures to achieve the goals.

On the other hand, the private forest owners association, e.g., Alliance of German Forest Owner Association (*Arbeitsgemeinschaft Deutscher Waldbesitzerverbände* (AGDW) is a nationwide organization of two million private and communal forest

[7] (Bundeswaldgesetz, 1975).
[8] http://forestportal.efi.int/lists.php?pl=60.05

owners in Germany[9]. The AGDW is composed of 13 state organisations across the states. Moreover, the Forestry Chamber Baden-Württemberg (*Forstkammer Baden-Württemberg Waldbesitzerverband e.V. (FOKA)*) acts as a representative, advocacy and service provider for the private and communal forest owners in Baden-Württemberg where about 230,000 forest owners - rural communities, cities, forest farmers and large private family farms exist. They cultivate three quarters of the forest in Baden-Württemberg, which is over one million ha.

The Forestry Association in Baden-Württemberg also supports different projects, e.g., the climate fund project KoNeKKTiW (Competence Network climate change, crisis management and transformation of forest ecosystems), launched in May 2014, which targets private forest owners to better prepare for the changes of their forests due to climate change (FVA, 2014).

2.3.2 Forest management in normal situation

One of the practical aspects in forest management is harvesting. It refers to the process of cutting trees and delivering them from the forest to the sawmills, pulp mills and other wood-products-processing plants. The main components of timber harvesting in forests are: logging, felling, skiding and sorting (Wellburn & Kuhlberg, 2010). After sorting, the timber logs of different sizes and quality are piled up along the forest roads (*Frei Waldstraße*), from where they are sold and transported to the industries.

The choice of harvesting methods depends on the management practices of the region. A number of different harvesting methods exist in which trees are selected for removal based on a number of factors, including species, ownership type, local terrain, transportation accessibility, storage capacity, labour availability and equipment. (Sauter, Hehn, Breinig, & Siemes, 2009) described 20 different harvesting systems available in Baden-Württemberg. (FVA, 2005) also discussed some typical harvesting methods applied in Baden-Württemberg such as motor manual system, fully mechanised system, etc. Machines are only operated on skid-roads at distances of 20 or 40 metres, depending on the soil conditions.

2.3.3 Forest management after an extreme winter storm

After an extreme winter storm, a large quantity of windthrow trees (i.e., salvages) becomes available within a short period of time. Therefore, a more strategic

[9] http://www.waldeigentuemer.de/

approach is required to deal with the situation as it significantly affects normal harvest practices.

Several studies proposed technical guides on conservation and harvesting of storm damaged timber in European forests (ECE/FAO, 2000), (Pischedda, 2004). An overview of the most relevant harvesting systems used in Europe after the storm of December 1999 was given by (Pischedda, 2004). Suitable harvesting systems for storm conditions are described in terms of the forest machines used and the location where the respective work is done. Finally, suitable methods for various scenarios of storm-damage conditions are proposed. (Odenthal-Kahabka, 2005) recommended such post storm salvage operation guidelines, on behalf of the state forest agencies of Baden-Württemberg and Rhineland-Palatinate, considering the experience following the storm Lothar. Figure 2.7 explains the typical post storm forest management operations and considerations observed in the state of Baden-Württemberg.

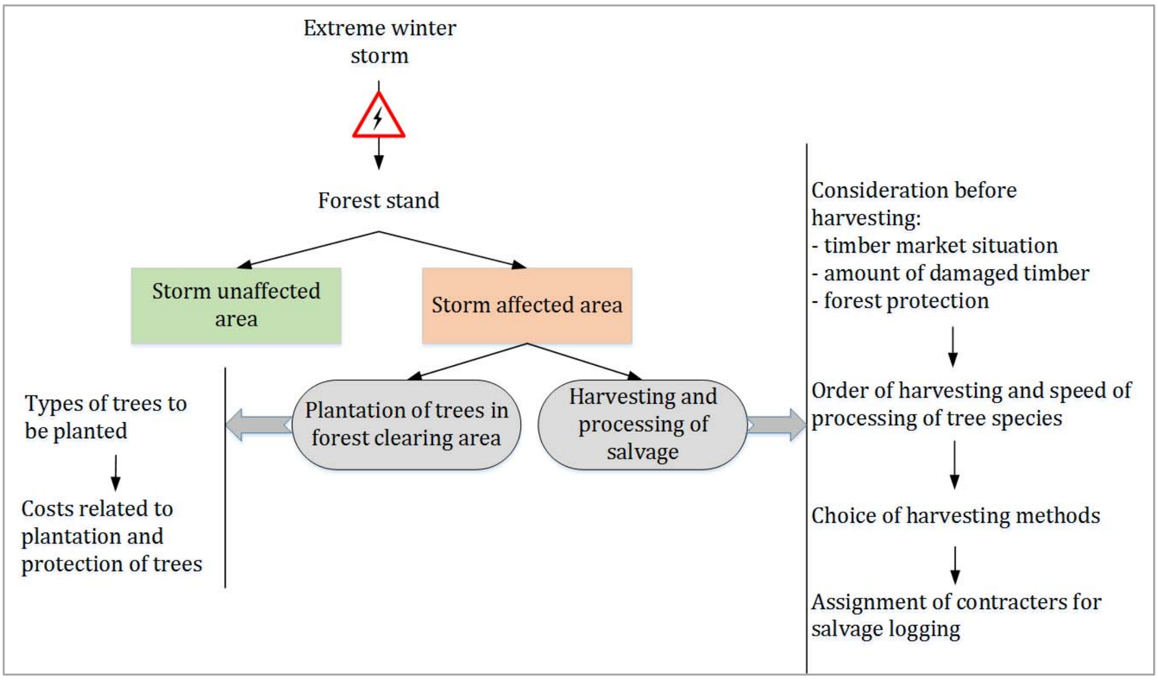

Figure 2.7: Forest management in storm affected areas in Baden-Württemberg

Parts of the forests in Baden-Württemberg are especially vulnerable to extreme winter storms (Section 1.1.2). A study by the Environment Ministry of Germany rated more frequent or more intense storm risk as 'very negative' because of an increase in storm damage (Schröter et al., 2005). It threatens forests immediately and directly, and exposes forest enterprises to an existential risk. Wood from storms enters into the market unplanned and in large quantities which leads to an intense decline in prices.

(Majunke, Matz, & Müller, 2008) suggested an increased storm damage in the future due to increased standing timber volumes and climatic conditions (e.g., increased winter precipitations with wet soils and a lack of winter frost) that favour storm damage. The impacts and crises following such a storm also pose serious problems because (Pischedda, 2004):

- Huge quantities of wood are damaged in forests,
- The harvesting operations become very hazardous due to the entanglement of the trees. Therefore, highly skilled workers are required,
- When the damage extends beyond a single region, transport costs are increased,
- More workers and equipment are necessary in order to reduce the time taken between harvesting and conservation,
- The establishment of storage sites has to be carried out as fast as possible which increases the associated labour and associated costs.

The impacts of storm damage are further intensified as:

- The quality of wood and salvage deteriorate,
- Extra costs associated with replantation of new trees in the forest clearing areas incur,
- The alternative decisions regarding the salvage operation lead to variation in monetary gains or losses.

However, the losses can be reduced by sustainable silviculture management before the storm event and by planning optimal salvage operations after the storm. For example, specific types of timber harvesting can mitigate increases in natural disturbance (T. P. Holmes, Prestemon, & Abt, 2008b). The pre-emptive harvest of live trees may lessen the severity of future events, thereby providing benefits beyond timber market values. Following a large disturbance event, forest managers may temporarily switch from harvesting live, to killed and mortally damaged trees (i.e., salvage logging) that remain commercially viable (Sims, 2013).

Therefore, in modelling economic impacts, forest management and salvage operation decisions need to be taken into account. Based on the experiences during previous storms, typical scenarios can be built to understand the impact. Additionally, alternative forest management scenarios would enable decision makers to evaluate the outcome of their strategies.

2.3.4 Related data source

2.3.4.1 Overview of data

Several forest and forest management related datasets, environmental and other considerations are required to assess the impacts of extreme winter storms on forest resources. These datasets and related assumptions are described in this section. Other datasets required for the assessment of windthrow vulnerability are described in Section 3.2.3 and Appendix 2.

2.3.4.2 Forest area

The forest area in each district in Baden-Württemberg can be calculated using the GIS analysis on forest land cover dataset. The low, medium and highly vulnerable forest areas are identified based on the vulnerability assessment using the Weight of Evidence (WofE) method (Chapter 3). Generally, the trees located in highly vulnerable forest areas would experience more severe damage than in the low vulnerable areas. Therefore, the storm affected forest areas in each district are calculated assuming a sum of 90% of high, 50% of medium and 10% of low vulnerable forest areas. Similarly, storm unaffected forest areas are the aggregation of the rest highly (10%), medium (50%) and low (90%) vulnerable forest areas. Such assumptions are based on the foresters' experience on previous post extreme storm situations in the forests in Baden-Württemberg.

2.3.4.3 Forest clearing areas

Forest clearing areas are storm affected areas where trees are damaged and reforestation is needed. Here the losses are determined not only by the windthrow trees and the cleaning up of storm affected areas but also by the costs associated with the preparation of soil, plantation of new trees species and loss of future potential timber values.

The tree plantation cost incurs as the forester has to plant new tree species in forest clearing areas in order to maintain forest ecology and to restore the forest reserve immediately after the storm. It is basically the one-time investment cost which is calculated per ha basis. According to Karlsruhe forest office[10], average planting cost is about 15,000 Euro/ha. Moreover, the security or protection cost of plants involves installation of fences and other protection measures against wild animals. Such costs generally incur until the plants are mature and resistant enough against wild animal

[10] Karlsruhe forest office delivered different forest management practice related data, which are not publicly available. These datasets are used in analysing the economic impacts in Chapter 5.

attacks. On an average, the security costs of plants are approximately 1000 Euro/ha/year during the first five years.

2.3.4.4 Growing stock

According to FAO[11], the total growing stock of timber in Germany is 3492 million m^3, with an annual change of 315 m^3/ha. In Baden-Württemberg, it is assumed to be between 200 and 400 m^3/ha. The third NFI reports the average growing stock in Baden-Württemberg is 377 m^3/ha which is higher than the nation-wide average of 336 m^3/ha (Kändler & Cullmann, 2014). Growing stock is required to estimate average timber volume in storm affected and unaffected areas.

2.3.4.5 Timber growth rate and thinning rate

The forest growth and thinning rate depends on the type of tree species, location, climatic condition, forest management strategies, etc. According to the third NFI, the average forest growth rate and thinning rate within the forests in Baden-Württemberg is 12.29 m^3/ha/year and 11.61 m^3/ha/year, respectively (Kändler & Cullmann, 2014). They have slightly reduced compared to the second NFI, which was 13.7 m^3/ha/year and 13.04 m^3/ha/year, respectively (Kändler & Cullmann, 2014).

Within the forest clearing area, not only the live timber, but also future potential timber value is lost, assuming that the trees would have continued to grow in case no storms would have occurred. This potential loss of value can be calculated considering the net timber growth rate which is 0.68 m^3/ha/year according to the third NFI (Kändler & Cullmann, 2014).

2.3.4.6 Timber price

Timber price depends on tree species, section of tree, size and quality of timber, terrain and accessibility of tract, location, etc. Different tree parts (e.g., round wood, industrial wood and wood residue), having different usage and quality are subject to different prices.

(Bauhus, 2010) analysed the historic development of the quantity and price of round wood, industrial wood and energy woods of a deciduous (Beech or *Buche*) and a coniferous (Spruce or *Fichte*) tree at the forest road within the state forests. The average Beech price was comparatively low between 2001 and 2006 (after the Lothar storm), but showed an increasing trend before falling slightly in 2009. The

[11] http://www.fao.org/docrep/013/i1757e/i1757e.pdf, p. 268.

price of Spruce also reduced dramatically in 2001 and showed price variation until 2004. Afterwards, the price increased until 2007, then reduced again (Figure 2.8).

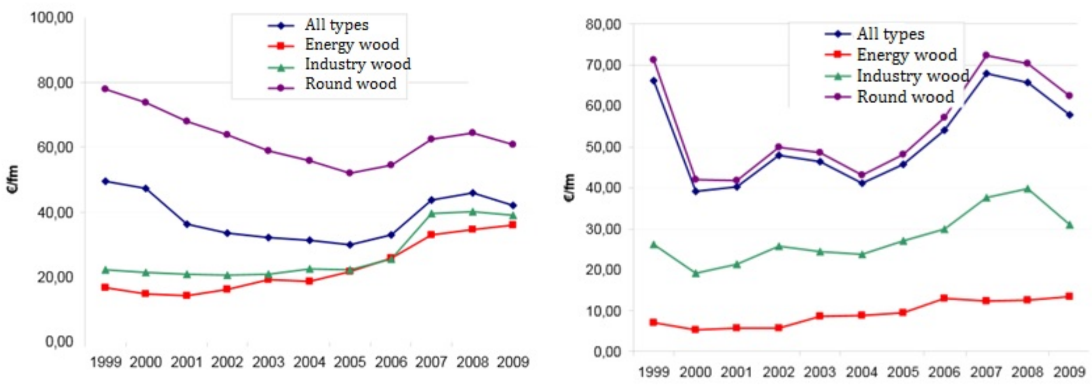

Figure 2.8: Development of wood price (left: Beech, right: Spruce) in Baden-Württemberg[12]

(Thrän, Edel, Seidenberger, Gesemann, & Rhode, 2011) also calculated the average price of forest residue and merchantable wood, which is approximately 57 – 76 Euro/Fm[13] and 76 – 102 Euro/Fm, respectively, in Germany. They suggested a price increase of 2% per annum.

In this research, the average price of industry and energy wood of the coniferous and deciduous trees, as observed by (Bauhus, 2010) and an annual increase of 2% for the next 20 years, as suggested by (Thrän et al., 2011) is considered.

2.3.4.7 Salvage price

Generally, after an extreme winter storm, the salvage price is lower than the timber price, mainly due to reduced wood quality and excess supply. (Prestemon & Holmes, 2004) found a reduction of 80 - 90% following hurricane Hugo due to degradation. (de Steiguer, Hedden, & Pye, 1987) found southern pine beetle mortality caused a 25 – 75% reduction in the value of timber. After the windstorm Klaus in January 2009 in the south-western region of France, the price of damaged timber decreased in 30% due to quality loss (Nicolas, 2009). In Germany, following the storm Vivian in 1990, wood prices sank by 50% which put the small private forest owners more at risk (Zebisch et al., 2005). After the storm Lothar in 1999, salvage timber flooded

[12] Translated after (Bauhus, 2010).

[13] One Fm (Festmeter) corresponds to one cubic meter (m^3) of solid wood mass, with no gaps in the layers.

the market, leading to a drastic decrease in timber price, e.g., prices for round wood dropped by at least 30% (ECE/FAO, 2000).

2.3.4.8 Harvesting cost

Harvesting cost includes costs associated with the felling, extracting and processing of trees. Exact cost depends on the location of timber and accessibility, volume of timber to be harvested and technology used, etc. According to Karlsruhe forest office, an average harvesting cost in Baden-Württemberg is about 16 – 26 Euro/m^3, which includes a felling cost of approximately 10 – 18 Euro/m^3 and extraction and processing cost of roughly 6 – 8 Euro /m^3. Other costs include an administrative cost of around 2 Euro/m^3.

2.3.4.9 Demand and supply elasticities

The timber markets in Baden-Württemberg must be regarded as slightly elastic[14] or inelastic (Hartebrodt, 2005). It is observed that the small round wood price elasticity of demand, related to the increased volume of supply, quickly leads to substantial price declines. (R. C. Abt & Ahn, 2003) observed that the price elasticity of salvage demand after forest disturbances is – 0.5. According to (Adams & Haynes, 1996), elasticity of supply with respect to price is 0.43 and with respect to inventory volume is set to 1.0. (Koch, Schwarzbauer, & Stern, 2013) studied private forests of different sizes and discovered an average price elasticity of supply of 0.81. (Bolkesjø, Solberg, & Wangen, 2007) found the overall price elasticity of supply to be 0.93 for non-industrial private forest owners in Norway.

(Schwarzbauer, 2007) investigated the influence of salvage cutting on timber prices and reported that a raw wood price elasticity of -0.4 (Mantau, 1987), and -0.025 (Bergen, Löwenstein, & Olschewski, 2002) was considered. (Hölscher, 2005) examined the impact of disturbances on the interconnectedness of regional standing timber markets in Germany. But the immediate elasticities of raw wood price against disturbances were not specified.

The price elasticities of demand and supply with respect to timber or salvage markets is not available for Baden-Württemberg. However, based on the market situation and experts' opinion, the price elasticities of demand and supply is assumed to be - 0.5 and 0.8, respectively in this research. Moreover, some sensitivity

[14] Elasticity is the sensitivity of consumers' reactions to external changes in prices and income. If the price or income effects are greater (less) than the quantity effects the elasticity will be greater (less) than one, (Wagner, 2012). Further illustration of price elasticities of demand and supply is given in Section 4.2.3.

analysis is applied to evaluate the effects of changes of price elasticity of demand (e.g., -1, -0.5, 0 and 0.5) on determining the salvage price.

2.3.4.10 Discount rate and time

The discount rate refers to the rate at which money in the future is calculated at present time (James, 1996). Different discount rates give different present values and it should be obvious that the larger the discount rate, the lower the value in today's money. The discount rate is used as analogous to the interest rate to calculate the net present value of a service or product. (Zhang & Pearse, 2011) concluded that it is very difficult to determine how much a society as a whole should discount future over present values because the market interest rates are influenced by a varying allowance of risk, expected inflation, distortion of the tax system and other market imperfections.

The use of a discount rate and its valuations are made according to the German Commercial Code (HGB) and are regulated by law[15]. The discount rates are also published monthly by the German Central Bank[16]. Generally, the average of the interest rates over the last seven years is used to avoid strong short-term volatilities. Considering the average interest rate in Germany over the last seven years (2008 - 2015), a discount rate of 4.35% is calculated (Mercer, 2015). Assuming that the current level of interest rates remains unchanged[17], following forecasted interest rates can be determined as of 28.02.2015: 3.79% on 31.12.2015, 3.10% on 31.12.2016 and 2.59% on 31.12.2017 (Mercer, 2015). In forest related impact studies, e.g., (Hartebrodt, 2004) used a discount rate of 4.5% in analysing storm damage on small-scale forest enterprises in the south-west of Germany, and (Prestemon & Holmes, 2008) suggested a base rate of 4% to assess the impacts due to fires in the US.

Therefore, in this study, considering the historic interest rate, the current economic situation of Baden-Württemberg and related literature, a discount rate of 4.35% per annum is assumed. Moreover, due to the uncertain nature of discount rate, the effect of the discount rate on model outcomes and salvage values would be evaluated using alternative rates, e.g., 2%, 4%, 6% and 8%.

[15] The law does not fix what rate to be used for specific regions (http://www.gesetze-im-internet.de/hgb/index.html).

[16] https://www.bundesbank.de/Navigation/EN/Statistics/Money_and_capital_markets/Interest_rates_and_yields/Discount_interest_rates/discount_interest_rates.html

[17] However, recently the interest rates in Germany have been reduced to less than 1%.

2.3.4.11 Forest regeneration

A certain percentage of harvested timber or salvage (mostly the branches or crowns, dead wood and weak wood) has to be left in the forest due to ecological reasons, mainly for the purpose of regeneration. According to Karlsruhe forest office, about 20% of the total salvage is intentionally left for this purpose and the rest (80%) is brought to the market.

2.3.4.12 Stolen salvage

After a catastrophic storm, certain amount of salvage is stolen from the forests. In some areas, where the forest surveillance is weak and the road accessibility is better, people bring unauthorised vehicles to steal large quantities of valuable salvage. Unfortunately, forest offices cannot monitor this illegal logging. Karlsruhe forest office assumes that about 1-2% of salvage is stolen after the occurrence of an extreme storm.

2.3.4.13 Marketable salvage

All salvage cannot be brought to the market immediately because of excess supply as well as shortage of resources (e.g., manpower, machines required for salvage collection, etc.). The decision on how much salvage is to be sold depends on the forest owner's or manager's view on demand supply balance (i.e., salvage price, elasticities of demand and supply, etc.). Based on discussions with the foresters and their experiences during the previous storms, it is assumed that 50% of the salvage could be brought to the market within the first year, while in the second, third, fourth and fifth year, the rest of 20%, 10%, 10%, and 10% salvage could be sold, respectively.

2.3.4.14 Salvage degradation factor

The quality of salvage deteriorates with time. The rate of degradation depends on the type of tree, geographic location, extreme event type, whether the salvage is infected with insects, etc. Based on extended literature study, (Prestemon & Holmes, 2008) suggested a net volume discount factor of 0.99 after 1 year, 0.89 after two years, 0.58 after three years, 0.22 after four years and zero after five and later years in analysing the economic consequences of a public salvage project in southwest Oregon. Unfortunately, such empirical study or data is not available in the context of Europe, Germany or Baden-Württemberg. However, the Karlsruhe forest office confirms that such degradation rate is also applicable, considering the similar climatic conditions in the forests in Baden-Württemberg.

2.4 Further research steps

The theoretical discussion, structural overview and statistical analysis of different aspects of forest resources and forest management in the state of the Baden-Württemberg provide the basis to analyse the vulnerability of forest resources and to assess corresponding economic impacts.

Economically significant extreme winter storms typically occur with low probabilities in locations that are not well known in advance (T. P. Holmes, Prestemon, & Abt, 2008a). For this reason, the forest areas that are most likely to experience damage based on the environmental conditions present in the state of Baden-Württemberg are identified in **Chapter 3**. After describing the effects of wind on trees, a comprehensive literature review on the assessment of storm damage, determining factors of windthrow, as well as several modelling approaches and their characteristics are defined. Later, the empirical WofE model that serves to analyse the windthrow vulnerability is systematically described. Finally, multiple model outcomes are evaluated and validated in order to prepare the final posterior probability map of the vulnerable forest areas in Baden-Württemberg.

3 Analysis of Vulnerability of Forest Resources

3.1 Wind effects on trees

The wind effects on trees can induce windthrow, a situation when a tree is uprooted or broken at the trunk due to wind. Two distinct types of windthrow are defined based on the frequency of occurrence and magnitude of damage:

- Catastrophic windthrow refers to infrequent (e.g., 20 year return period) storms with remarkably strong winds which cause severe damage to both stable and unstable tree stands. It inflicts substantial ecological and economic impacts (Gardiner et al., 2010). The main factors causing this type of windthrow are wind speed and direction, as well as local topographic conditions.
- Endemic windthrow occurs more frequently (e.g., 1-5 year return period) and is caused by trees having a low stability and increased exposure due to recent harvesting or thinning, making them more vulnerable to recurring peak winds (Lanquaye, 2003). The strong influence of site conditions and silviculture practices on endemic windthrow makes this phenomenon easier to predict than catastrophic windthrow.

In both cases of strong wind conditions, wind excitations of trees may lead to damage: branches, crowns and stems can break or trees can be thrown, when stems and roots plate overturn (Quine & Gardiner, 2007).

This research aims to analyse catastrophic windthrow, which causes the damage mainly through uprooted trees or breakage at stems. The detailed physical process of windthrow is described in (Zielke, Bancroft, Byrne, & Mitchell, 2010), (M. J. Schelhaas, Kramer, Peltola, Van der Werf, & Wijdeven, 2007).

Figure 3.1 describes the different types of wind effects on trees and the possible damages.

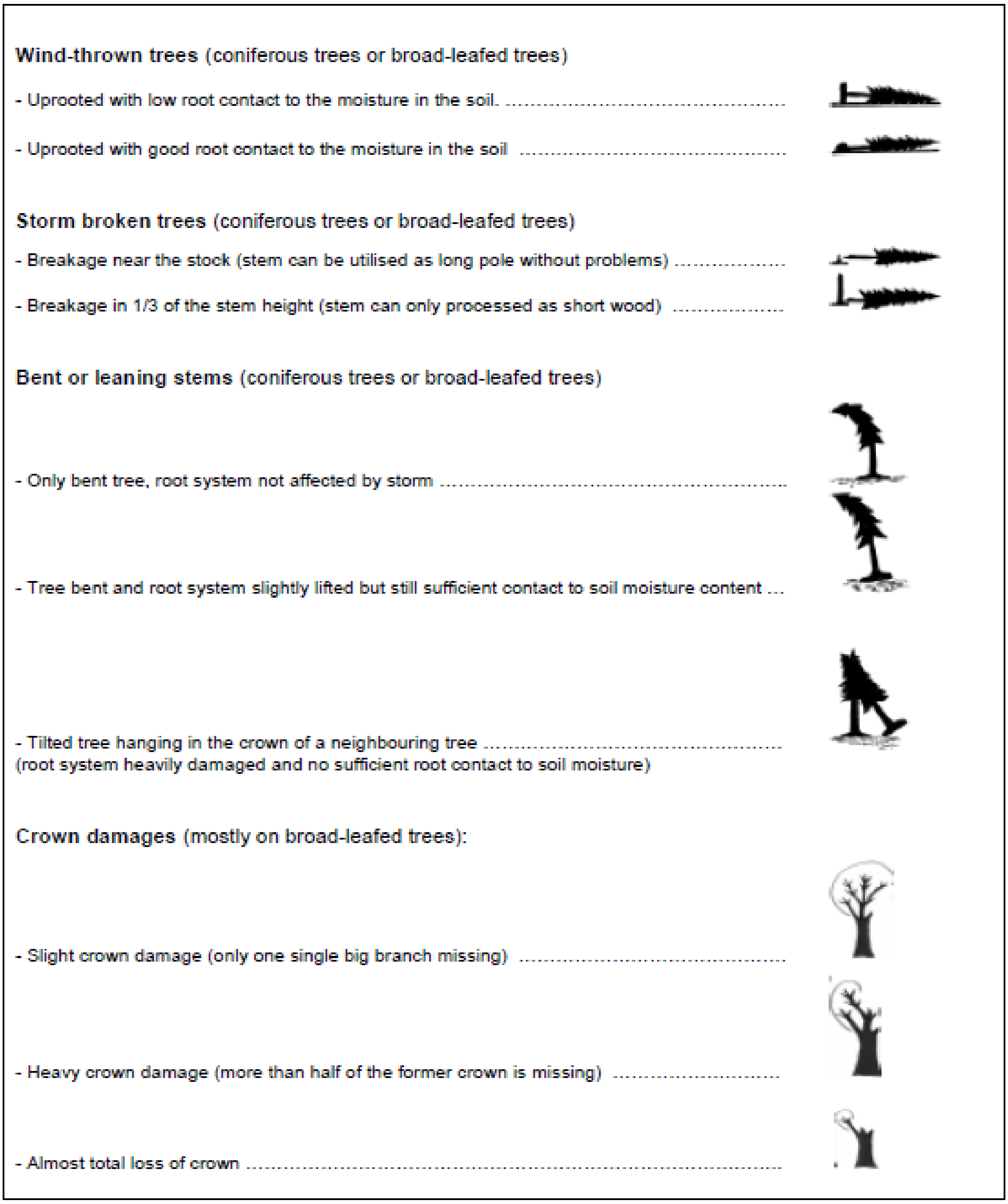

Figure 3.1: Short description of wind effects on trees and possible damage[1]

[1] (Pischedda, 2004).

3.2 Literature reviews

3.2.1 Assessment of storm damage

In assessing storm damage, the complex interaction between wind and trees is important to understand, and so numerous interdisciplinary research studies have been performed in various spatial and temporal scales, across different countries.

(Jiao-jun et al., 2004) reviewed the publications of three international conferences on 'wind and trees' organized by the International Union of Forestry Research Organizations – at Heriot-Watt University, Scotland in 1993 (Coutts & Grace, 1995), University of Joensuu, Finland in 1998 (Peltola et al., 2000) and University of Karlsruhe, Germany in 2003 (Ruck, Kottmeier, Matteck, Quine, & Wilhelm, 2003). They concluded that the research largely addresses the state of the art of aerodynamic interaction of wind and trees, mechanics of trees under wind loading and adaptive growth, tree's physiological responses to wind and a risk assessment of wind damage for forests. However, (Jiao-jun et al., 2004) identified the needs for further research in the fields of wind damage to natural forests, wind-driven gap formation and forest dynamics[2], the effects of changes resulting from wind disturbances on ecological processes of forest ecosystems and research regarding the management for wind-damaged forests.

Recently, (Schindler, Grebhan, Albrecht, Schönborn, & Kohnle, 2012) also reviewed the research progress in wind-tree interactions by highlighting the International Conference on 'Wind Effects on Trees' held at Albert-Ludwigs-University of Freiburg, Germany in 2009. The main focus was to understand the behaviour of the trees in high winds as well as the occurrence of storm damage and it's impacts on forests (Mayer & Schindler, 2009). They also summarized the research gaps regarding spatial and temporal scale of severe storms, the interaction of high impact wind and trees at a local scale, the interaction between high-impact winds and complex forest structure as well as impacts of climate change on the regional risk of wind damage.

(M. Hanewinkel et al., 2011) summarized 35 papers to review the most important factors in assessing storm damage. The spatial and temporal scale of these factors varies greatly from single tree assessment to regional analysis. The choice of the scale mainly depends on data availability. (M Hanewinkel et al., 2010) also carried

[2] Forest dynamics describes the changes in forest structure and composition over time including its behaviour in response to anthropogenic and natural disturbances (Pretzsch, 2009).

out a comprehensive literature overview regarding variables that influence storm damage. Both studies discussed different models and different ways of integrating them into decision support systems.

3.2.2 Determining factors of windthrow

According to former research, factors influencing the vulnerability of forests to winter storms can be divided into four groups: (a) weather, (b) site conditions, (c) topographic conditions and (d) tree and stand characteristics (D. Schindler, K. Grebhan, A. Albrecht, & J. Schönborn, 2009), (Quine & Gardiner, 2007). Different models have been studied over the years to determine the importance of these variables in quantifying the vulnerability of forests to wind storms; they have provided valuable insight into the behaviour of trees during windstorms.

The main factors associated with windthrow can be described in three levels of detail: (a) individual tree, (b) forest stand[3] and (c) site level. At each level, the factors influence differently. For example, at tree level, factors such as height, crown size and rooting structure are important. At the stand level, common variables include species composition, height, density and silviculture treatments. At the site level, soil conditions and topographic exposures are assessed for their contribution to, or correlation with, windthrow damage (Table 1).

[3] Forest stands, usually 1-4 ha, are covered by relatively uniform species' composition or age.

Table 1: Factors influencing the wind effects on trees at three levels of detail

Factor	Representation of level of detail
Individual tree level: Species Individual tree characteristics (height, diameter at breast height (DBH), age) Rooting structure	
Stand level: Species composition Age class Height class Canopy and stand density Silviculture interventions	
Site level: Topographic exposure Elevation, slope, aspect Soil condition Geology	

This research will focus on the vulnerability assessment at the stand and site level, because detailed data at individual tree level is not available for the state of Baden-Württemberg. Moreover, due to forest management structure and operations, decision support tools are more appropriate at stand and site level levels. Therefore, all factors at these levels will be critically analysed and tested to identify the most influencing variables in windthrow vulnerability assessment.

3.2.3 Modelling approaches

3.2.3.1 Overview of models

Wind damage vulnerability modelling approaches are dependent on the type of windthrow under investigation. Three main categories of vulnerability modelling approaches are identified in related literature (Schindler, Grebhan, et al., 2012), (M. Hanewinkel et al., 2011):

- The expert system method, where research and literature reviews are carried out and experts are consulted to identify variables that are strongly linked to tree and stand vulnerabilities. Forests or sites are then classified according to this knowledge. The expert system is suitable for small regions, but as the area increases, it is difficult to make assumptions about conditions that hold true for large study areas.
- The other two model based approaches, e.g., mechanistic (and semi-mechanistic) and statistical (or empirical) models have been extensively applied worldwide in the assessment of the vulnerability of forests over the past decades.

3.2.3.2 Mechanistic and semi-mechanistic models

Mechanistic models attempt to characterize the physical process of stem failure and uprooting through controlled experiments. These models allow researchers to make a hypothesis, develop experiments to reveal system components, analyse results and to make predictions for new scenarios (Gardiner, Peltola, & Kellomäki, 2000). (M. J. Schelhaas et al., 2007) investigated the interaction of trees within stands to incorporate a stand density factor accounting for the support provided by surrounding trees. Similarly, (Hale, Gardiner, Wellpott, Nicoll, & Achim, 2012) included a series of competition indices based on the size of the tree and distance to the nearest neighbour. With the use of these indices, vulnerability of individual trees with varying spatial distribution within the stand can be estimated. The most widely used mechanistic and semi-mechanistic models include ForestGALES, HWIND and FOREOLE (Gardiner et al., 2008).

Mechanistic models generally require high quality input data to parameterize the model and submodels, which can be expensive to acquire, if it is available at all (M. Hanewinkel, Peltola, H., Soares, P. and González-Olabarria, J. R., 2010). For German forests, appropriate parameterization of tree species, soil types, terrain complexity, near surface airflow, etc. is not available for wind damage risk assessment (Dirk Schindler, Karin Grebhan, Axel Albrecht, & Jochen Schönborn, 2009). Moreover, the methodological basis of these models is to assess risk for single-species stands on homogeneous terrain, thus, its capability to correctly predict wind damage on the stand level in spatially complex forests is rather limited (Dirk Schindler et al., 2009).

3.2.3.3 Empirical or statistical models

Empirical or statistical models reveal the correlation between the occurrence of wind damage (i.e., the dependent variable) and in some cases the magnitude of damage, to a number of independent variables including tree, stand and site characteristics as well as meteorological data (Schindler, Bauhus, et al., 2012). Such models calculate the probability of damage, given the presence or absence of the statistically most significant variables.

Many studies concerning the assessment of the vulnerability of forests to windthrow utilize an empirical, data driven approach, usually in the form of a regression model. Ideal datasets for empirical modelling should be both spatially and temporally accurate and representative[4]. Furthermore, such models require a large sample size for fitting and testing. Windthrow occurrence is a rare event, making it difficult to obtain comprehensive long term datasets for important dynamic variables, e.g., tree and stand characteristics, in addition to the associated meteorological conditions that caused the damage.

Different types of empirical models have been used in windthrow vulnerability assessment both in Germany and in other countries. A concise list of recently used empirical models to assess windthrow damage is given in Table 2.

Table 2: Different empirical models used in windthrow assessment

Empirical models	**References**
Logistic Regression Models	(Scott & Mitchell, 2005), (Jalkanen & Mattila, 2000), (Klaus, Holsten, Hostert, & Kropp, 2011), (Valinger & Fridman, 2011)
Weights of Evidence method (WofE)	(Dirk Schindler et al., 2009), (Schindler, Grebhan, et al., 2012)
Classification and Regression Trees (CART)	(Albrecht, Hanewinkel, Bauhus, & Kohnle, 2012), (Dobbertin, 2002)
Generalized Linear Models (GLM)	(Klaus et al., 2011), (Albrecht et al., 2012)
Generalized Linear Mixed Models (GLMM)	(M. Hanewinkel, Breidenbach, Neeff, & Kublin, 2008), (Albrecht et al., 2012)
Generalized Additive Models (GAM)	(Schmidt, Hanewinkel, Kändler, Kublin, & Kohnle, 2010)

[4] Meaning that the sample data is adequate to represent the natural behaviour of the variables and permit good estimations.

Neural Networks (NN)	(M. Hanewinkel, 2005), (M. Hanewinkel, Zhoub, & Schilla, 2004)

In most of the studies, one single storm event is considered. (Albrecht et al., 2012) explained that only a limited number of studies have analysed damage from more than one storm event concurrently.

The choice of a particular model depends on the scale, extent of data as well as the aim of the study. For example, (Schmidt et al., 2010) used a GAM model to identify tree level characteristics associated with wind damage, but did not include information about the stand.

A data-driven model such as the Weights of Evidence method provides an objective approach to predict windthrow by revealing statistical relationships to various environmental predictors. The WofE model is particularly suitable for large regions and heterogeneous forest structures. The forest stands of Baden-Württemberg - having a complex and variable structure as well as a very heterogeneous topography and soil compositions - justify WofE as the most suitable method (M Hanewinkel et al., 2010). It is also a highly popular data driven technique, due to its statistical approach, which can be understood by non-specialists. Moreover, the availability of software packages that are integrated with the GIS facilitate performing the calculation on space (A. Ford & Blenkinsop, 2008).

In a GIS-based estimation of winter storm damage probability, (Schindler, Grebhan, et al., 2012) tested a number of predictor variables for their significance in the weight of evidence model, concluding that soil type and moisture, geology, forest type, topographic exposure and gust fields greater than 35 m/s were the most important factors available for assessing damage probability at the state level. The authors stated that CORINE[5] land cover data was crucial for the analysis given that important tree and stand level data were unavailable.

3.3 Description of WofE model

3.3.1 Origins of the method

The phrase 'Weights of Evidence' has likely been used for many centuries and can be traced back at least to 1878, where it was used in the Oxford English Dictionary

[5] (Keil, Kiefl, & Strunz, 2005).

to describe the influence of information on the outcome of a decision (Good, 1985). In more recent years, the term has referred to a method based on Bayesian theory to statistically quantify the significance of certain predictors, which, when weighted and combined, can be used to determine the probability of an occurrence or event.

In the late 1980s, geologists developed a WofE methodology for potential mineral deposit mapping using GIS (Agterberg et al., 1993; Bonham-Carter, Agterberg, & Wright, 1989). The conceptual basis was to measure the spatial association between geological and physiographical features (GIS layers with classes) with known mineral occurrences and produce 'weights' for each of the statistically significant classes. More recently, several studies have applied this method to model other dichotomous spatial phenomena, e.g., windthrow vulnerability (D. Schindler et al., 2009), (Schindler, Grebhan, et al., 2012), landslide susceptibility (Poli & Sterlacchini, 2007), (Pradhan, Oh, & Buchroithner, 2010), wildfire risk (Romero-Calcerrada, Novillo, Millington, & Gomez-Jimenez, 2008), species distributions (Wildman & Peters, 2008), habitat quality assessment (Romero-Calcerrada & Luque, 2006), land cover classification using remotely sensed data (Li & Song, 2012), and mineral prospectivity (Carranza, 2009).

3.3.2 Mathematical definitions

WofE follows the Bayesian theorem to calculate posterior probability of an event or occurrence, which is simply a prior probability updated to account for the presence of certain evidentiary knowledge. This method provides the statistical framework to quantify the strength of spatial association between training data sets (e.g., windthrow occurrence) and evidence themes (e.g., forest type, soil acidity, wind speed, etc.).

In this research, a total number of 3,221 training points are derived from LUBW 2000 and CLC 2000 damage class datasets under the condition that the damage areas are greater than one ha. Furthermore, 11 evidence themes covering weather, site, topography and forest conditions are considered. Then the significance of these themes is tested through formulation of multiple models in order to understand the important factors influencing the development of WofE modelling. Finally, the WofE method has been applied to create posterior probability maps to predict the windthrow vulnerability.

In WofE, a point represents an occurrence of the phenomena of interest, which in this case is windthrow. For modelling purposes, each point is considered to occupy a small unit cell. This model expresses probabilities of a unit cell containing a point occurrence, point D. The number of unit cells containing a known occurrence of a point, $N(D)$, is counted and divided by the total number of unit cells comprising the study area, $N(T)$. This is the **prior probability** of an occurrence when no information is available to influence the probability and is expressed as (Bonham-Carter et al., 1989):

$$P(D) = \frac{N(D)}{N(T)} \quad 3.1$$

In the case that conditionally independent (CI) evidence is present in a study area, the Bayes rule may be applied to update the prior probability $P(D)$. For example, given that a predictor, E occupies $N(E)$ number of unit cells that also contain a known occurrence of windthrow, $N(D/E)$, the conditional probabilities can be stated as:

$$P(D|E) = \frac{P(D \cap E)}{P(E)} = P(D) * \frac{P(E|D)}{P(E)} \quad 3.2$$

$$P(D|\bar{E}) = \frac{P(D \cap \bar{E})}{P(\bar{E})} = P(D) * \frac{P(\bar{E}|D)}{P(\bar{E})} \quad 3.3$$

$P(D|E)$ expresses the probability of occurrence D given the presence of evidence E; conversely, $P(D|\bar{E})$ expresses the probability of D given the absence of evidence E.

Another important concept in the WofE methodology is the odd, $O(D)$, which is defined as a ratio of the probability that a unit area contains a point with a given evidence $P(D)$, to the probability that the same unit area does not contain a point given $P(\bar{D})$. Probabilities can be transformed into odds following this relationship, $O = P/(1/P)$, so that (Bonham-Carter et al., 1989):

$$O(D) = \frac{P(D)}{P(\bar{D})} \quad 3.4$$

$$O(D|E) = O(D) * \frac{P(D|E)}{P(\bar{D}|E)} \quad 3.5$$

$$O(D|\bar{E}) = O(D) * \frac{P(\bar{D}|E)}{P(\bar{D}|\bar{E})} \quad 3.6$$

Furthermore, weights are derived based on the natural logarithm of the conditional probabilities which exploit the spatial overlap between training points (e.g., windthrow areas) and the evidential themes (e.g., forest type, soil acidity, etc.) (Agterberg et al., 1993; Bonham-Carter et al., 1989). For convenience, weights are calculated probabilities transformed into logits, the natural logarithm of odds. For evidence maps, weights are calculated for each evidence class based on their presence or absence of cells occupied by the training sites. In the case of binary evidence, a positive weight is the result of an association between the presence of the evidence and the training points. Conversely, a negative weight will represent an association between the absence of evidence and the training points. Weights are presented as natural logarithms because they are more easily interpreted in log linear than in an ordinary probability expression (Kemp, Bonham-Carter, & Raines, 2006).

In the form of logit, weights of each class within a particular evidence theme can be added together to create a total weight for that particular evidence theme.

$$W^{+} = ln \frac{P(E\,|D)}{P(E|\,\bar{D})} \qquad 3.7$$

$$W^{-} = ln \frac{P(\bar{E}\,|D)}{P(\bar{E}|\,\bar{D})} \qquad 3.8$$

The overall measure of spatial association of evidence and training points is given by the difference between W^{+} and W^{-} and is known as contrast, C. If there is no spatial association between training points and evidential theme, the weight will be 0.

Assuming conditional independence (CI)[6] among evidential themes, the posterior logit that a unit cell contains an occurrence of windthrow given n evidential themes can be expressed as:

$$L\big(D \,\big|\, E_1 \& E_2 \& \ldots E_n\big) = L(D) + W_1 + W_2 + \cdots + W_n \qquad 3.9$$

To express windthrow as a probability, the relation of odds and probabilities mentioned above can be used:

$$P(D|E) = \frac{exp(L(D|E))}{1+exp(L(D|E))} \qquad 3.10$$

The produced **posterior probabilities** should not be interpreted in absolute terms; instead, a classification based on a relative ranking needs to be used (Schmidt et al., 2010).

3.3.3 Predicting windthrow vulnerability

3.3.3.1 General approach

The WofE modelling approach suggested by (Dirk Schindler et al., 2009; Schindler, Grebhan, et al., 2012) is improved to create windthrow vulnerability maps in the

[6] The degree of CI is tested is section 3.3.3.6.

state of Baden-Württemberg. For this purpose, the forest land cover data at 30 metres resolution is used. These datasets provide an additional class for windthrow damaged areas which were not considered by previous studies. Moreover, these land cover datasets significantly increase the number of training points, since the minimum detection size for windthrow is less than one ha, which was five ha in earlier studies. The extreme winter storm hazard data is collected at a 1 km x 1 km grid for different return periods (Hofherr & Kunz, 2010) and thus enables modelling at a higher spatial resolution than in previous studies.

Several assumptions are made to model the windthrow vulnerability and are based on the literature review described in Section 3.2. For example,

- Coniferous forests (especially Norway Spruce) are more vulnerable to windthrow hazard,
- Forests where root growth is limited by soil conditions such as high moisture or acidity content will be more vulnerable to windthrow,
- In general, forests that are less exposed (sheltered areas) to the wind will experience less damage.

The methodology proposed by (Agterberg et al., 1993) within the framework of Spatial Data Modeller for ArcGIS and Spatial Analyst (ArcSDM) is applied in this study (Appendix 1). Eight steps are involved in the prediction of windthow vulnerability. The general workflow of the methodology is illustrated in Figure 3.2.

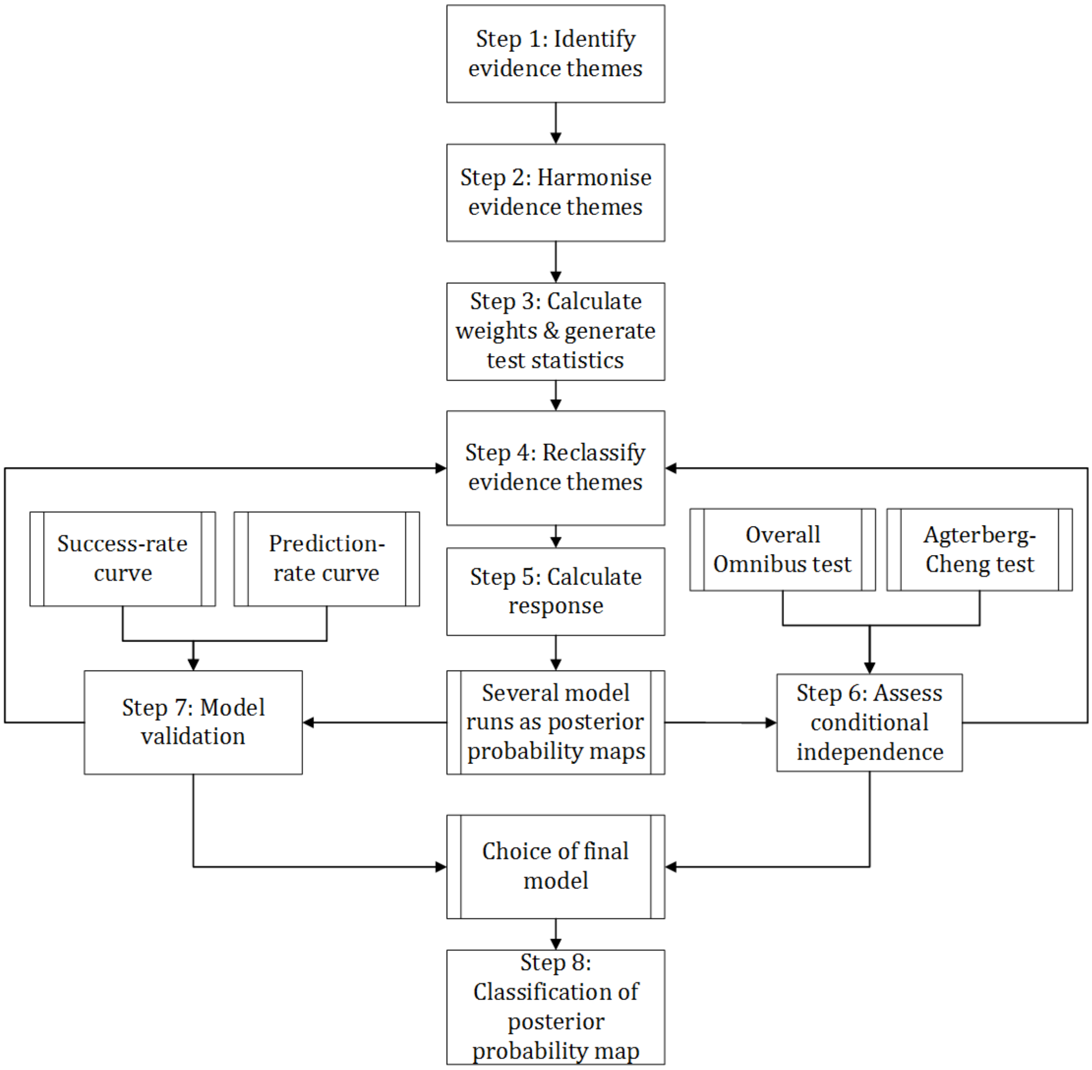

Figure 3.2: Description of the WofE methodology

3.3.3.2 Identify and harmonize evidence themes (step 1, 2)

The forest evidence theme originates from the LUBW 1993 land cover dataset containing three classes for the forest type (i.e., deciduous, coniferous and mixed forest). The site evidence layers include datasets of soil type, moisture content, acidity and geology, which are derived from the Water and Soil Atlas of Baden-Württemberg. The topographic variables used in this study include elevation, slope, aspect, and distance limited topographic exposure (TOPEX)[7] indices. The mean wind speed data of Karlsruhe Atmospheric Mesoscale Model (KAMM) is the weather related evidence theme.

[7] As recommended by (Ruel, Pin, & Cooper, 1998), distance limited TOPEX is chosen as the exposure index. It is calculated using the GRASS software (GRASS, 2012).

In total, 11 evidence themes having a different number of classes are considered in the development of WofE model. An overview of all these themes along with the original number of classes is described in Table 3.

Table 3: List of evidence themes and corresponding number of classes

Evidence groups	**Evidence themes**	**Original number of classes**
Forest	Forest type	3
Site	Soil type	29
	Soil moisture content	21
	Soil acidity	13
	Geology	14
Topography	Elevation	Continuous
	Slope	Continuous
	Aspect	Continuous
	Distance Limited TOPEX (Sum of 8 distance limited TOPEX grids)	Continuous
	Modified distance limited TOPEX indices (8 grids for each cardinal direction)	Continuous
Weather	Wind speed	Continuous

These evidence themes and training points are collected in different spatial scales and resolutions. They need to be harmonized to the same spatial resolution, format and scale. A detailed overview of the characteristics of these datasets and their harmonization procedures is given in Appendix 2.

3.3.3.3 Calculate weights and generate statistics (step 3)

In this step, weights and other statistics for each class of an evidence theme is formulated, e.g., in order to understand the spatial association and to measure the uncertainty associated with the statistics. Spatial association between training points and classes of evidential themes are measured by weights[8] and contrasts. Contrast, C, is the difference between positive (W^+) and negative (W^-) weights for each class within the evidence layer and represents an overall measure of the spatial association between the training points and the evidence class. The final weights reveal the predictive capability of each class.

Studentized contrast, Stud(C), the contrast divided by the standard deviation of contrast, is a student t-test that provides a measure of uncertainty associated with contrast. A threshold value is specified at the early stages of the modelling process to define the acceptable level of uncertainty. The value of 1.96, which corresponds to a confidence level of 97.5%, is selected for this model, where Stud(C) values that fall below this threshold are automatically grouped into a single class by the software as performed in other studies (Dirk Schindler et al., 2009).

3.3.3.4 Reclassify evidence themes (step 4)

The statistics generated in the previous step provide parametric measures for generalizing and reclassifying evidence into binary and multi-class themes. No manual classification was performed for the categorical data of forest, soil type, moisture, acidity and geology. For other evidence themes, the classes with Stud(C) values lower than 1.96 were grouped together automatically during the weight building process, otherwise the class value was left unchanged (Schmitt, 2010). The results of the weight and other statistics of the most significant themes are illustrated in Appendix 3 (Table A – Table E). For example, concerning soil acidity, damage is strongly associated with 'strong and deep acidic soil near moderately acidified soil' (class 11) with a Stud(C) value of 23.2[9].

Soils with higher moisture content exhibit different levels of association with damage. The most significant soil moisture class is 'fresh to temporarily fresh soils' (class 14) with a Stud(C) of 10.57. Soils of lower moisture content are generally negatively associated with damage (Appendix 3, Table B).

Soil type also proved to be an important variable, e.g., soil class 'the sand and clay mixture alternating with loam over clay' (class 203) having a Stud(C) of 14.26 shows strong association with storm damage. 'Peat soils' (class 112) are negatively associated with damage having a corresponding weight of -2.08. Other negatively

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[8] The 'Calculate Weights' function of the ArcSDM toolbox produces a database file (.dbf) containing the weights and statistics for each class of the input evidential theme.

[9] Other association of less significance is with 'very strong and deep acidic soils' (class 10) and 'strongly acidic soils with the main root zone at high base saturation in the subsurface' (class 12). The Stud(C) values are 4.87 and 2.1, respectively.

associated soil types are, e.g., ‘sand and clay mixed soils’ (class 103), ‘peat and sand mixed with clay’ (211), etc. having a weight ranging from -1 to -2.2 (Appendix 3, Table C).

In the geology evidence theme, the most dominant lithostratigraphic units, e.g., ‘keuper’ (class 7), ‘bunter sandstone’ (class 2) and ‘limestone/loess’ (class 8) display the largest association with storm damage, with Stud(C) values of 12.60, 11.41 and 11.39, respectively (Appendix 3, Table D).

The continuous topographic themes, e.g., elevation, aspect and slope showed little association with damage patterns, whereas the distance-limited TOPEX to the west (TOPEX_W) show a greater association with damage (Figure 3.3). This can be explained by the observation that the main direction of the wind from extreme storm is westerly (Heneka, 2006; Schmidt et al., 2010), and the forest areas exposed to this direction are likely to experience stronger winds.

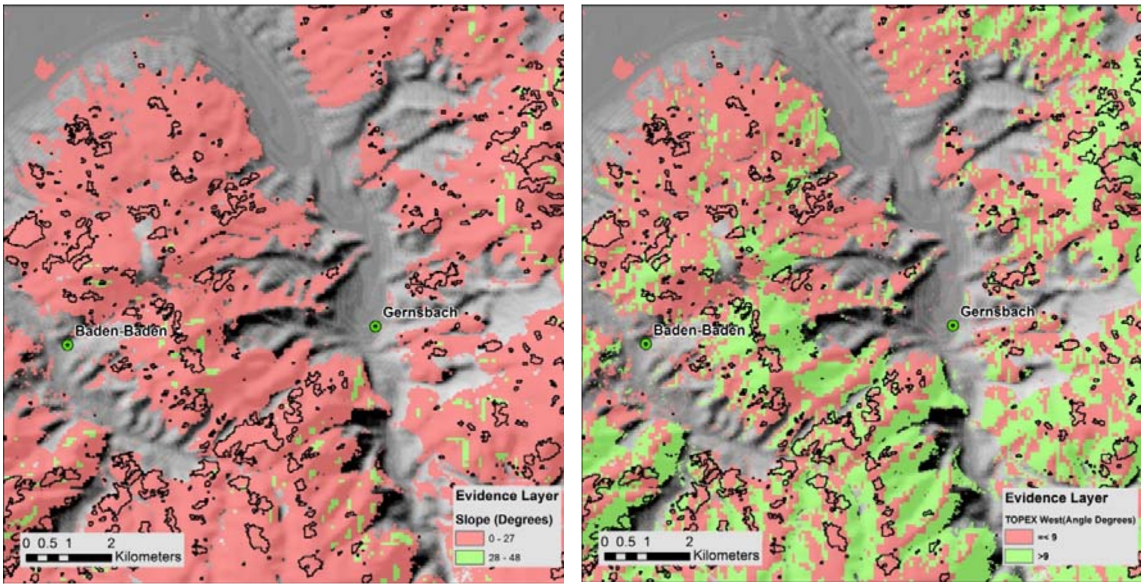

Figure 3.3: Forest damage areas in land cover datasets overlaid on slope (left) and topographic exposure to the south (right)

Regarding forest type, a strong association between the coniferous forest class and the wind damage training points are revealed. Conversely, both deciduous and mixed forests show a strong negative association with damage training points. The Stud(C) values for the ‘coniferous’ (class 1), ‘deciduous’ (class 2) and ‘mixed’ (class 3) types are 23.92, -15.25 and -13.71, respectively.

In literature, a widespread damage has been associated with wind gust speeds over 35 m/s (D. Schindler et al., 2009), (Schindler, Grebhan, et al., 2012), (Usbeck et al., 2010), therefore, a binary layer representing mean gust speeds greater than this speed is created (Figure 3.4). This layer however shows a relatively weak association with damage. The contrast and Stud(C) were both low and alteration of the maximum gust speed does not improve the results (Appendix 3, Table E).

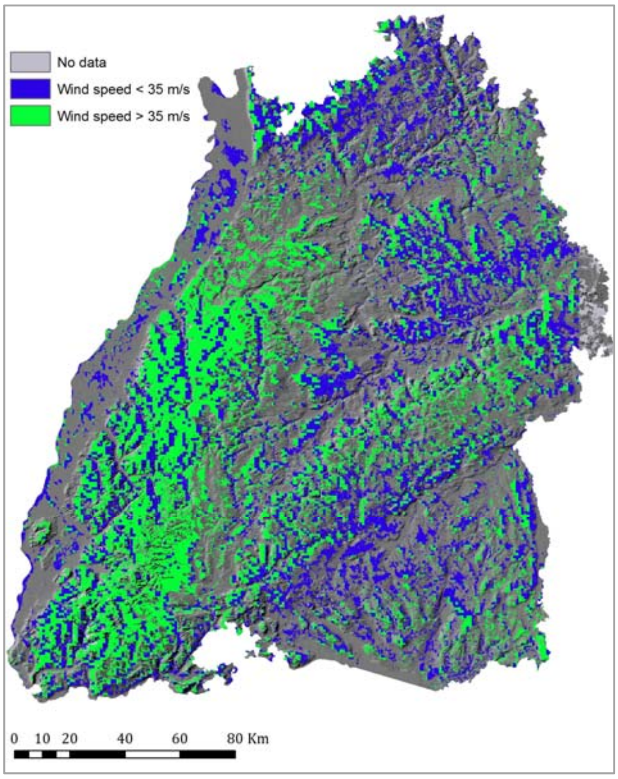

Figure 3.4: Reclassification of gust wind speed into two binary classes

3.3.3.5 Calculate response (step 5)

In this step, continuous scale posterior probability maps are prepared. The first map on the model 1 (M1) is produced from the selected 8 evidence themes and their associated weights. An overview of the statistical summary of all the models (M1 – M11) is given in Appendix 4.

One important assumption made in WofE modelling is that evidence themes and classes are conditionally independent (CI); otherwise an inflation of posterior probability may occur. Since the posterior probability maps do not consider the CI among layers, further steps are required to ensure that evidence layers are not redundant. Although some degree of conditional dependence always exists between certain layers (especially environmental layers), tests can be applied to reveal how serious the assumption of CI is violated (Schmitt, 2010).

3.3.3.6 Assess conditional independence (step 6)

In the case that all evidence themes are independent, it is expected that the calculated number of windthrow occurrences will equal the observed number of occurrences (Schmitt, 2010). This, however, is rarely the case, as evidence themes derived from environmental factors will be inherently correlated to some extent. For this reason, 11 models are created to find out the best combination of evidence themes with the greatest conditional independence (CI) and highest accuracy; these models are presented in the Appendix 4 with statistics provided to evaluate CI within the response maps.

An **Overall Omnibus test** is performed to measure the degree to which conditional independence is violated between themes and between classes within single themes. The CI ratio can be calculated, with n as the number of training points and T as the sum of the posterior probabilities weighted according to the unit cell area, as:

$$CI = n/T \qquad 3.11$$

with CI values less than 1 indicating some conditional dependence between two or more datasets, but values less than 0.85 indicate a major problem as conditional dependence exists (Schmitt, 2010). The models M1 - M4 show a CI ratio less than 0.85, while the models M7 - M11 indicate minimum amount of CI.

The **Agterberg-Cheng (AC) test** is the most reliable CI test (Schmitt 2010). Here, the number of calculated occurrences T is subtracted from the number of observed windthrow damages n, to reveal if the value is significantly greater than 1. This is a one-tailed test with a null hypothesis that T-n = 0 with the test statistic as:

$$AC = (T-n)/\ \sigma T \qquad 3.12$$

In the AC test, probability values greater than 95% or 99% indicate that the hypothesis of CI should be rejected, but any value over 50% indicates some level of conditional dependence (Schmitt, 2010). Among the 11 models, the maximum probabilities exist in models M1 - M7 and they are not CI (as the probability is 1), while the models M8 - M11 show the minimum CI (see Appendix 4).

Finally, the overall CI value is prepared by rescaling the AC test from 0% - 100% which indicates the confidence whether the posterior probability is conditionally independent. For example, models M1 - M7 show 0% confidence that the posterior probability is CI, while M8, M9, M10 and M11 display approximately 16%, 4%, 28% and 68% confidence on CI, respectively.

Therefore, the CI tests performed in this step prove the acceptance of the models M8, M9, M10, M11. However, for certain tests, some of these models perform better than others, e.g., M11 apparently shows best results, since the difference between the calculated and observed windthrow occurrences (T-n) is minimum (20.70), conditional independence (CI) ratio is maximum (0.99), only 66% probability that model is not CI, and 68% confidence that the posterior probability is CI (see Appendix 4). But the validation of these models needs to be performed in order to justify and to accept one particular model and the corresponding posterior probability map.

3.3.3.7 Model validation methods (step 7)

Several validation methods, e.g., Success-Rate Curve, Prediction-Rate Curve and Blind Tests are performed to build confidence in the WofE model outcome (Schmitt, 2010).

The Success-Rate Curve (SRC) test provides a measure of how well a model predicts known windthrow damage (i.e., training points). For visual inspection, a success-rate curve is created by plotting the cumulative training points (%) on the y axis and the cumulative area (%) on the x axis. The area under the curve (AUC) gives an indication of the predictive accuracy of the model. Among the best performing CI tests of models M8 – M11, M8 displays the maximum AUC of 70.5%. Therefore, considering the accuracy and different CI tests performed in earlier steps, M8 is the most reliable model. It considers four predictors, e.g., soil acidity, forest type, TOPEX west and wind gusts greater than 35 m/s.

Following the examination of the SRC, it is necessary to investigate how well the model predicted windthrow occurrence points that are not used in the training process. To assess this, Blind Tests (BT) are performed by utilizing subsets of the training data, and a curve similar to the SRC is created by plotting cumulative testing points (%) vs. the cumulative area (%), resulting in the Prediction-Rate Curve (PRC). It is performed after a four step methodology suggested by (Schmitt, 2010). The results of this test indicate that the training points are well represented.

3.3.3.8 Classification of posterior probability map (step 8)

The posterior probability values are ranged from 0 (min) to 1 (max). They should be interpreted as relative ranking of wind damage potential. (Fabbri & Chung, 2008) suggested to replace these values by classifying in ranks; they proposed methods to interpret and classify them, e.g., using a Cumulative Area Posterior Probability (CAPP) curve (Schmitt, 2010).

The classification of the final model (M8) is performed by plotting the cumulative area (%) vs. the posterior probability. Break points are selected where the curve rose sharply indicating significant change between probabilities classes (Figure 3.5). Three classes are defined and the breaks at 0.0022 and 0.0045 are selected as the class threshold. In the highest vulnerable class, approximately 18% of the forest is located whereas in the medium and low vulnerable class, about 20% and 62% of the forest is identified, respectively.

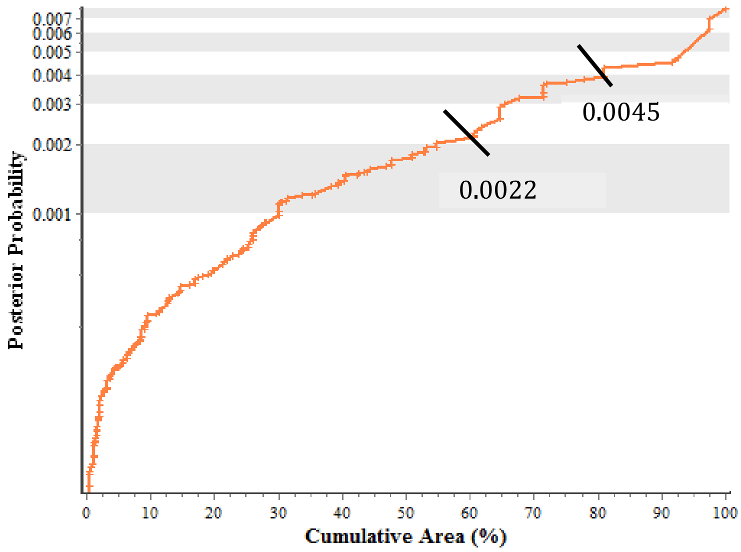

Figure 3.5: Cumulative Area Posterior Probability curve of final model (M8) used for classification

Finally, the classified posterior probability map of windthrow vulnerability (M8) with the least CI and highest accuracy is displayed in Figure 3.6. A careful visual inspection and GIS overlay reveal that the areas with high topographic exposure to the west, acidic soils and coniferous forest types exhibit highest damage probabilities.

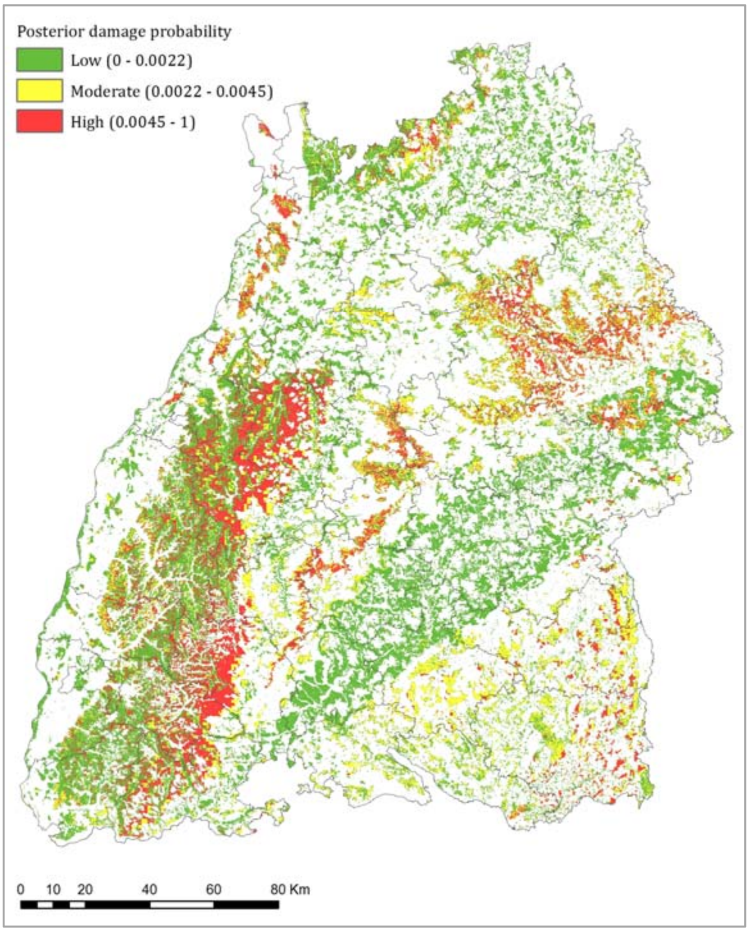

Figure 3.6: Posterior probability of damage due to an extreme winter storm

3.3.4 Discussion of results

The weight of evidence methodology produced raster grids of one ha unit area representing the posterior probabilities of damage due to a stochastic winter storm. The prior probability of the grids is updated to posterior probability by summing all weights from each of the evidence themes (logits converted into probability) at the grid location.

Posterior probabilities are calculated for approximately 14,035,596 ha of forests in the state of Baden-Württemberg. A classification based on CAPP reveals that the majority of the forests (62%) are located within a low damage class, while the moderate damage probability class covers 20% and the highest damage probability class covers 18% of the area (Figure 3.7).

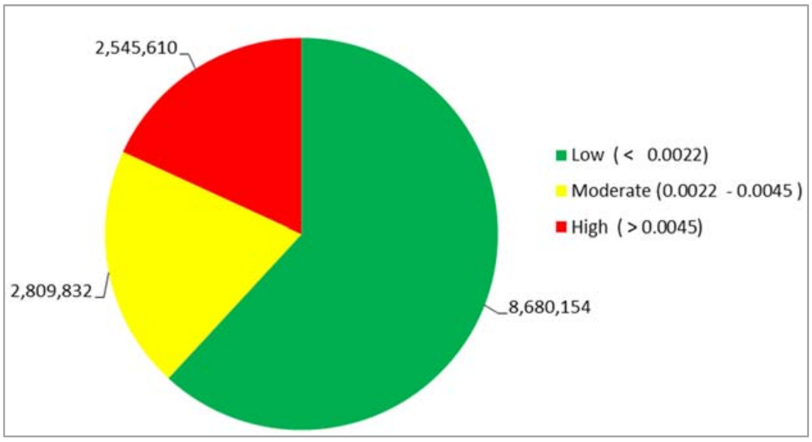

Figure 3.7: Share of low, medium and high vulnerable forest areas

The posterior probability map depicts a similar damage pattern as in the actual LUBW and CLC damage data (highest damage in northern Black Forest and the eastern districts of Heidenheim and Ostalbkreis), with the highest proportions of forest in the high damage class located in the northern Black Forest and stretching eastward. A significant exception to these results is found in the southern portion of the Black Forest in the districts of Schwarzwald-Baar-Kreis and Breisgau-Hochschwarzwald, where the model predicts high damage probabilities, but very low proportions (< 1%) of total forests that might be actually damaged (as observed in LUBW and CLC damage data); this can be identified in the lower right example in Figure 3.8. This signifies that the area is highly vulnerable to future extreme winter storms.

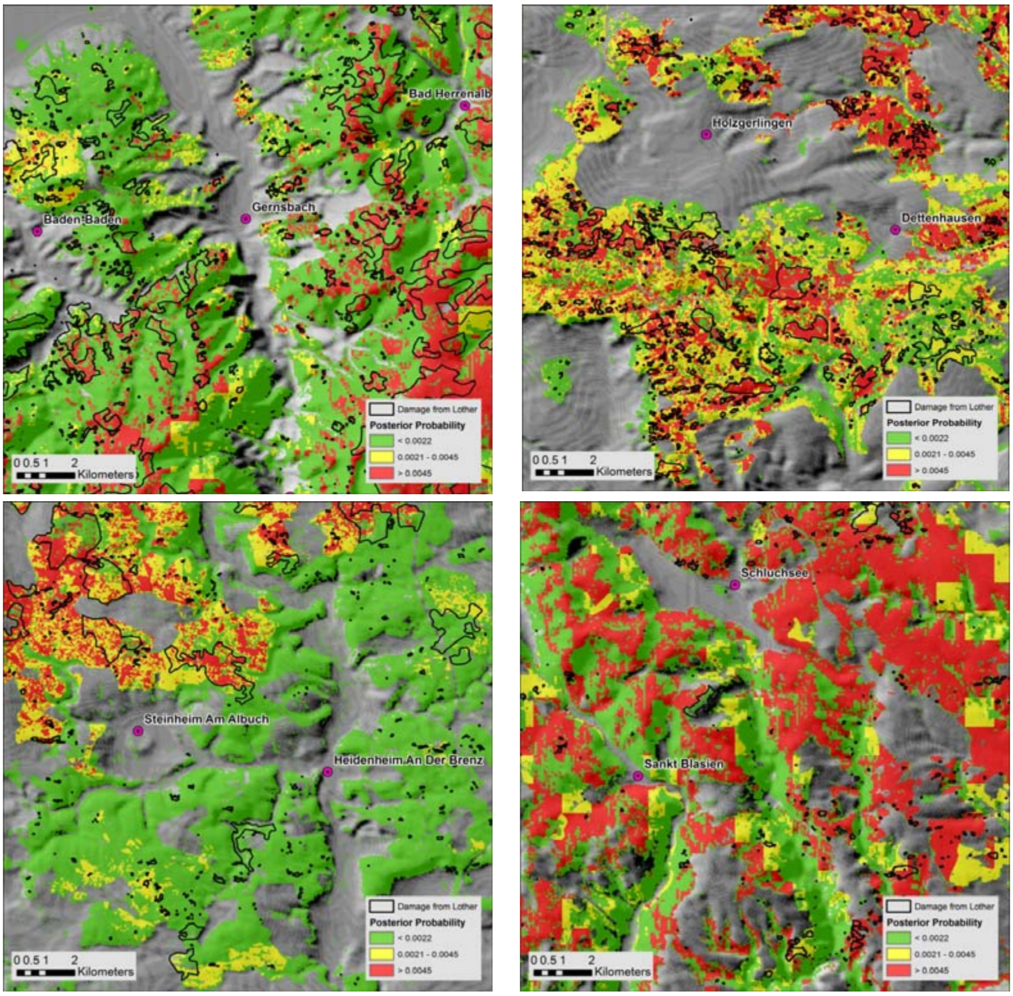

Figure 3.8: Four examples of WofE results in Baden-Württemberg: northern Black Forest (top left), central Baden-Württemberg (top right), northern Swabian Mountains (*Schwäbische Alb,* lower left) and southeastern Black Forest (lower right)

The outcome of the WofE model is used for investigating the windthrow probability across Baden-Württemberg at one ha resolution and is meant to provide scientists and policy makers with a state-wide view of probable damage patterns of different magnitudes considering the present conditions. With the delineation of such vulnerable areas, further economic impacts can be analysed and evaluated, e.g., by considering typical post storm forest and salvage (windthrow) management practices, as well as by developing alternative policies and scenarios.

Many limitations do however exist in the WofE modelling approach, because such empirical modelling only reveals important correlations between dependent and independent variables and not necessarily causality. Some of the evidence themes such as geophysical layers are inherently highly correlated with one another: soil type, e.g., is related to acidity, moisture content and underlying geological conditions. When these layers are assessed together in the WofE methodology, the assumption of conditional independence between themes as laid out in the model may become false, resulting in an over fit of the model. Due to the relatively large extent of the study area and the complexity of the terrain, correlating damage with specific orographic[10] conditions proves difficult. For example, the forests of Baden-Württemberg also experienced considerably different weather conditions during the single Lothar event (Schmidt et al., 2010).

Simulated wind speeds do not prove to be a significant predictor in the model. This is in agreement with other studies which have investigated windthrow damage in central Europe (Schütz, Götz, Schmid, & Mandallaz, 2006), (Schindler, Grebhan, et al., 2012), (Albrecht et al., 2012). The severity of damage also depends on the duration of the event, maximum sustained wind speed and precipitation immediately prior and during the event (Mitchell, 2012). Therefore, further investigation on understanding the interaction of these factors over the duration of a storm is required.

The area under curve (AUC) gives an indication of the predictive accuracy of the model. For the final model (M8) considered in this research, the AUC was 70.5%, which is slightly lower (72.8%) than that found in the study of (Schindler, Grebhan, et al., 2012). They tested a number of predictor variables for their significance in the model, concluding that soil type and moisture, geology, forest type, topographic exposure, and gust fields greater than 35 m/s were the most important factors available for assessing damage probability at the state level.

This study has tested 11 different models with varying combinations of predictor variables (evidence themes) to understand the most important variables. The data regarding the preparation of training points and evidence themes is significantly improved compared to previous studies. The final model (M8) uses 3,221 known windthrow affected areas as training points in conjunction with four evidence themes, i.e., soil type, forest type, topographic exposure in direction of west and gust wind speed greater than 35 m/s to produce the posterior probability maps of windthrow vulnerability in the state of Baden-Württemberg.

3.4 Further research steps

The posterior probability map prepared in this chapter will be used as an important input parameter into the system dynamics model introduced in Chapter 5, where

[10] Orography is the study of the topographic relief of mountains.

the economic impacts of such extreme winter storms in the forest resources in Baden-Württemberg will be assessed.

Before assessing impacts, a theoretical framework for modelling the impacts is introduced in **Chapter 4**. A literature review on impact assessment and research challenges in particular to the impact analysis in forestry is detailed. For such assessment, understanding the economics of salvage decisions, timber and salvage market reactions after the storm, as well as salvage modelling aspects is important. Finally, in order to justify the use of system dynamics for impact modelling, the components of system dynamics and its integration into the economic modelling and GIS are described with different applications.

4 Assessing Economic Impacts with System Dynamics

4.1 Framework of economic impacts

4.1.1 Impact assessment

Each extreme event is unique and the impacts it causes can present enormous challenges for economic modelling of disasters (Okuyama, 2007). In identifying current critical issues in modelling economic impacts, (Okuyama, 2007) described the importance of the consideration of time, space and counteractions. Because, time represents the dynamic nature of the impacts that evolve, the spatial distribution of impacts helps to identify critical areas of interest and the counteractions help to formulate the economic resilience or adaptation strategies, etc. He also stressed that to overcome the greatest challenge in future research on economic modelling of disasters, researchers need to focus on the interface between theory, model development and disaster management practice.

Natural disturbances can trigger acute forest damage[1] and interrupt or impede the flows of goods and services provided by forest ecosystems (T. P. Holmes et al., 2008b). This could be caused by abiotic (e.g., volcanoes, flood and droughts), biotic (e.g., pests, invasive plants) and mixed (e.g., wildfire) events that show different characteristics in terms of type of damage, rate of spread of damage, spatial scales, impact magnitude and time, etc. The economic costs and losses are influenced by these factors, as well as by forest management strategies and decisions regarding salvage operations.

The direct damages, e.g., physical destruction of infrastructures, resources and networks such as forest trees, buildings, transportation, etc. and indirect damages due to the disruption of economic activities are the central components of modelling the impacts. Indirect damages are difficult to quantify and have been given less importance in literature. (Albala-Bertrand, 1993) claimed that indirect disaster effects are "often unimportant for the economy and society as a whole and rapidly

[1] Acute forest damage is defined as any sudden and severe forest damage involving an amount of timber which cannot be handled without bringing in additional resources to the affected area (FAO, ECE, & ILO, 1995).

counteracted within the disaster area", since "in-built societal mechanisms may prove sufficient to prevent most potential indirect effects on the economy and society".

The impact modelling is performed at micro or macro-economic levels. Most famous macro-economic impact models are Input-Output (IO) models, social accounting matrices and general equilibrium models. These models are statistically rigorous, they can provide stochastic estimates and have forecasting capabilities but they require very detailed time series and cross section datasets (Okuyama, 2007). They often do not consider the dynamics, geographic references and interactions within the system or sector under investigation. A comprehensive analysis of these modelling approaches, advantages and limitations, as well as different applications were elaborated by (Chang & Miles, 2004; Menny, 2011; Okuyama, 2009; Okuyama & Chang, 2004).

(Chang & Miles, 2004) proposed a system dynamics model, based precisely on the observation from empirical evidence which is not considered in the macro-economic model mentioned above. The aim of their model is to integrate dynamic processes in the model design, instead of working with static equilibriums. In contrast to the macro-economic models, this approach is much better grounded in theory. The main problems are to identify key processes and to integrate them into the modelling, while unimportant processes should be excluded. Therefore, detailed empirical evidence on the economic and social processes after extreme events is necessary.

A key element of a system dynamics model is feedback effects. One event A may have an effect on B, but B can again potentially trigger A, which enables the modelling of dynamic effects. (Borst, Mechler, & Werner, 2008) attempted to model the potential consequences of an earthquake on the loss and recovery of textile companies in greater Istanbul. (Dauelsberg & Outkin, 2005) presented a system dynamic approach to model economic impacts such as lost revenues and lost sales arising from disruptions due to an infectious disease outbreak to critical infrastructures such as energy and transportation in a metropolitan area. They also investigated the potential results of various response and protective measures. Additional studies on natural disturbance related impact analysis in forestry, based on other approaches, are described earlier in Section 1.1.4.

The literature review helps to identify the most critical aspects of impact assessment which are the type of impact and extreme events to be analysed, scale and extent of analysis, modelling approaches, etc. (Figure 4.1).

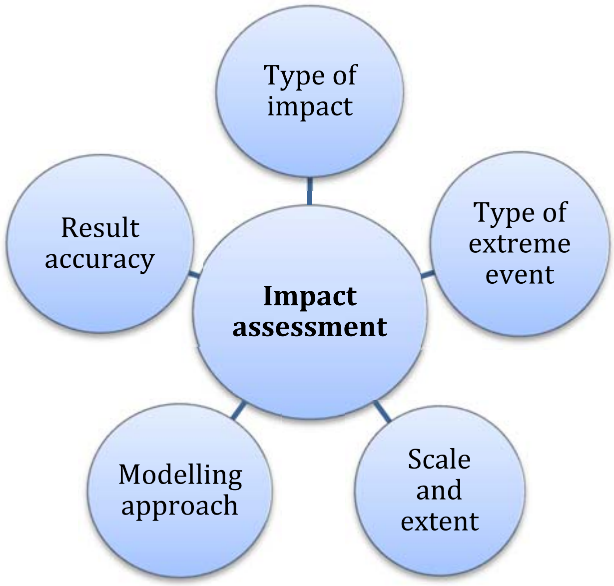

Figure 4.1: The critical aspects to consider in impact assessment

Considering all of these aspects, this study aims to propose a system dynamics based simulation model to analyse micro-economic impacts of direct losses in forests due to stochastic extreme winter storm. For this reason, the outcome of the WofE model, i.e., a map of posterior probabilities of vulnerable forest areas and associated factors are considered as inputs into the system dynamics model.

4.1.2 Impact assessment in forestry

Extreme winter storms affect the forest resources and ecosystems - damaging trees and ecosystems and thus causing significant economic losses (see Section 1.1.2 and Section 2.3.3). The timing and spatial extent of extreme winter storms are highly stochastic and difficult to predict. Economically significant events typically occur with low probabilities in locations that are not well known in advance (T. P. Holmes et al., 2008a). Therefore, an analysis of economic impacts due to such events is important. It can help the policy makers, forest administrators and private owners to understand the causes and consequences of salvage operations as well as to set priorities and evaluate trade-offs between live timber harvesting and salvage operations. This way it is possible to analyse optimal salvage/windthrow management alternatives and to plan the silviculture management strategies by observing the most influential factors and simulating their effects under different economic, temporal and spatial conditions. Moreover, an early assessment also helps systematic management of storm risk through insurance solutions. Many timber and forest based industries, e.g., sawmills, biomass based power plants, etc. can also plan alternative options.

Similar to other economic systems, forestry is connected to space and time. So, its economic assessment is sensitive to spatial, temporal and sectoral scales. Therefore, impact assessment needs to be conducted across multiple scales, and decision makers need to be informed of the sensitivity of economic measures to the scale at which economic models are applied. Since an extreme winter storm can have huge impacts on markets for goods and services obtained in forests, timber losses and damages affect economic equilibriums both through the extra timber salvaged from an event and through reductions in stocks of standing timber. Thus economic welfare is redistributed after a catastrophic forest disturbance, with some economic agents gaining (e.g., the consumers of wood products in the short term due to the reduced timber price) while others lose (e.g., producers of damaged timber as they have to sell the timber at a reduced price) (T. P. Holmes et al., 2008b).

The modelling of economic impacts is challenging as it also requires very detailed temporal data on different sectors. The uncertainty related to data and to the modelling result is also crucial. (T. P. Holmes et al., 2008b) identified four research needs in quantifying economic impacts:

- Economic models need to account for the complexity of the disturbance processes so that the efficiency and efficacy of management interventions can be realistically assessed.
- Non-linear dynamics and spatial diffusion[2] are challenging attributes of forest disturbances.
- Further development of statistical, econometric, mathematical and simulation models that consider management interventions across various temporal and spatial scales are also needed.
- Understanding non-market economic impacts would provide a larger knowledge base for improved management decisions.

Therefore, based on the literature review, the main challenges for assessing the economic impacts in forestry are summarized in Figure 4.2.

[2] Spatial diffusion process is applied to analyse the phenomena related to forest fire or disease outbreaks. Due to the characteristics of winter storms, such process is not considered to analyse the impacts of extreme winter storms.

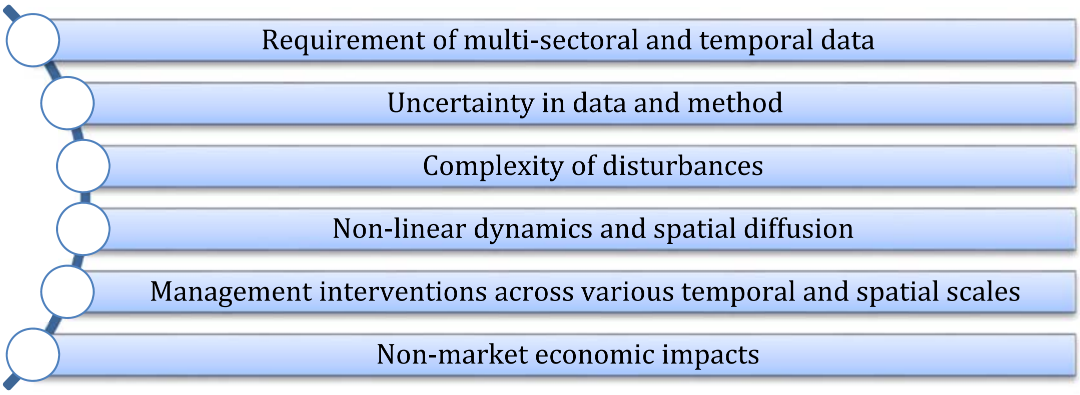

Figure 4.2: Challenges in assessing economic impacts in forestry

This research addresses most of the identified challenges. For example, the complex interaction of winter storms with trees is thoroughly investigated considering the statistically-based weight of evidence method, which provides a very good basis of identifying the windthrow vulnerability. Multi-sectoral and temporal data is collected from the forest offices and related literature. The non-linear dynamics of different factors associated with impact assessment are inspected using the system dynamics simulation method.

Non-market damages to livestock, water and recreational services, damages to private property values and to human health are becoming increasingly influential in forest management (Zhang & Pearse, 2011). Some of them are technically difficult to quantify while others are offered as public services. Some forest economics literature tried to quantify the non-market values using different methods such as (a) revealed preference or indirect methods (e.g., travel cost approach, hedonic method, etc.) and (b) stated preference or direct methods (e.g., contingent valuation technique, survey, etc.) (Wagner, 2012; Zhang & Pearse, 2011). However, the assessment of non-market impacts is beyond the scope of this research.

The decisions regarding forest management and salvage operation as well as associated economic factors are also carefully reviewed. In analysing economic impacts due to storm damaged timber, (Pischedda, 2004) emphasized the importance of considering different economic aspects with a view to maintain the monetary value of round wood[3], by protecting its quality. Furthermore, the marketing strategies must be organized in order to control the sale of round wood and to prevent the depreciation of its value. Capital costs may be very important because the total costs of logging and storage (including transport, equipment,

[3] Round wood is the most expensive part of a tree (see Figure 2.5).

maintenance, etc.), as well as the value of the wood, may be tied up for a prolonged period of time, leading to a heavy financial burden. Therefore, the timber salvage operations need to be planned optimally. All these issues are considered in the impact assessment.

4.2 Timber salvage after winter storms

4.2.1 Economics of salvage decisions

An extreme winter storm leaves a huge quantity of salvage timber and partially damaged standing timber. Salvage operations follow partially different approaches than the normal timber harvesting (see Section 2.3.3). Wood flows remain more or less the same as in the case of normal harvesting, but the extra wood is exported to other regions or countries due to excess supply. After such events, forest managers may temporarily switch from harvesting live timber to killed and mortally damaged trees that remain commercially viable (Sims, 2013).

Economics of timber salvage decisions is critical. It varies among private and public forest owners. It is assumed that private owners aim to maximise profit or land value while public managers make decisions to maximise the value of timber and non-timber output. Salvage decisions for private owners depend on the price of timber, salvage degradation rate[4], age of stand during damage, etc. Public managers' decisions to salvage depend on non-timber impacts on salvage, distance to market, the expense of storage, species mix, timber quality, nature of damage, etc. (Prestemon & Holmes, 2008).

This research illustrates the salvage operation decision options from both private and public forest owners' perspective and evaluates how such different preferences influence to the assessment of corresponding impacts.

4.2.2 Key issues in salvage modelling

Salvage modelling can help private and public forest owners to evaluate the economic impacts of alternative timber salvage operations. For example, at maximum salvage effort, net economic welfare in the market might be higher, compared to delayed salvage operation or not salvaging at all. Therefore, alternative salvage options could help to mitigate the overall economic impacts arising from

[4] Salvage degradation rate depends on factors such as species, pre-storm timber quality, degree and nature of damage, etc.

catastrophic events. In this regard, both the public and private owners need to understand the price changes (e.g., timber and salvage) during the aftermath of a catastrophic winter storm in order to alter their salvage operation plans accordingly.

(Prestemon & Holmes, 2008) observed that delay, spatial extent, and impacts of timber demand are important factors in the dynamic modelling of salvage operations. Because,

- Delays regarding timber sales will reduce the quantity and quality of salvable timber through degradation. Research by (Prestemon, Wear, Stewart, & Holmes, 2006) quantifies how these kinds of delays may have resulted in real economic welfare losses in the timber market.
- Spatial extent of timber price dynamics depends on the scale of storms and the costs to transport materials between affected and unaffected regions.
- Timber demand impacts are not well understood. They may shift in both directions. For example, housing damage[5] may cause extra demand for timber which may increase the timber price. This way, owners in storm unaffected regions may suffer as well.

In this research, delays regarding salvage decisions are introduced through system dynamic simulation methods. The dynamics of salvage operations, i.e., when and how much of salvage would be brought to the market is determined through the decision on the yearly selling amount. The reduction of timber and salvage price due to deterioration of quality in time should also be studied. The spatial extent of timber price dynamics is partially considered[6], whereas the timber demand impacts on, e.g., the housing sector are not addressed. Demand impact analysis requires assessment of damage to the housing sectors which is out of the scope of this research. However, the historic average yearly timber demand is considered.

4.2.3 Timber and salvage markets

Timber is the dominant commercial product produced from forests. Supply and demand determine the value of timber - similar to other goods and services. After a storm, generally the market prices of salvaged timber are adjusted through supply and demand (Zhang & Pearse, 2011). Therefore, demand, supply and their

[5] It depends on the type of materials used to construct the houses.
[6] Assumptions related to price dynamics are explained in Section 5.1.2.

elasticities are important determinants in timber salvage operation decisions and thus in analysing the corresponding economic impacts.

Figure 4.3 (left) explains the basic concepts of demand and supply. In case of excess salvage immediately after the extreme storm, the supply curve shifts rightward (due to excess supply of timber). This has two effects: raising the equilibrium quantity, and lowering the equilibrium price. Such phenomenon is explained in Figure 4.3 (right). This concept is utilized to identify the market equilibrium price at different simulation years during modelling the impacts in system dynamics.

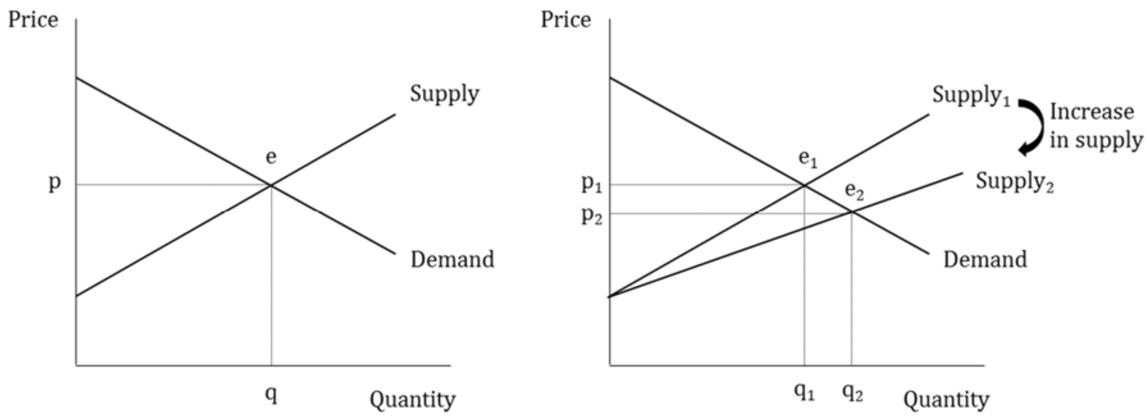

Figure 4.3: Market demand and supply curve (left), increase in supply causes to move the supply curve (right)

The concept of elasticity is useful to understand the dynamic response of supply and demand in a market. The elasticities of demand or supply can be defined as the responsiveness of the quantity demanded or supplied to a change in price (Zhang & Pearse, 2011). (Wagner, 2012) carried out a detailed discussion on different types of forest economy related demand elasticities (e.g., own-price elasticity, cross price elasticity, etc.) and the methods to estimate them. He defines elasticity as the percentage change in either price or income relative to the percentage change in quantity, holding everything else constant. So, the price elasticity of demand (E_d) is basically the percentage change in quantity demanded (Q_d) divided by the percentage change in price (P), e.g.,

$$E_d = \left| \frac{\%\ change\ in\ Q_d}{\%\ change\ in\ P} \right| \qquad 4.1$$

Price elasticity of supply (E_s) is the percentage change in quantity supplied (Q_s) divided by the percentage change in price (P), e.g.,

$$E_s = \left| \frac{\%\ change\ in\ Q_s}{\%\ change\ in\ P} \right| \qquad 4.2$$

The concept of price elasticities of demand and supply are required to assess the salvage price in different simulation years. Examples and assumptions on such elasticities are discussed in Section 2.3.4.

(Prestemon & Holmes, 2008) described how large scale natural disturbances affect timber markets and participants. They observed that due to an extreme storm, timber markets demonstrate a price decline due to excess of salvaged timber entering into the market that may continue to stay in market for a longer time. The salvage price effect occurs immediately after the disturbances (Prestemon & Holmes, 2004). In contrast, price and quantity impacts due to losses in timber inventory can last longer than the salvage period and depend upon the growth rate of subsequent inventory, i.e., the standing timber.

(Prestemon & Holmes, 2008) explain the effect of the salvage and inventory losses with a demand curve and three supply curves representing the three main epochs of timber market conditions following an inventory destroying large scale disturbance: pre-disturbance, during salvage and post-salvage equilibrium (Figure 4.4).

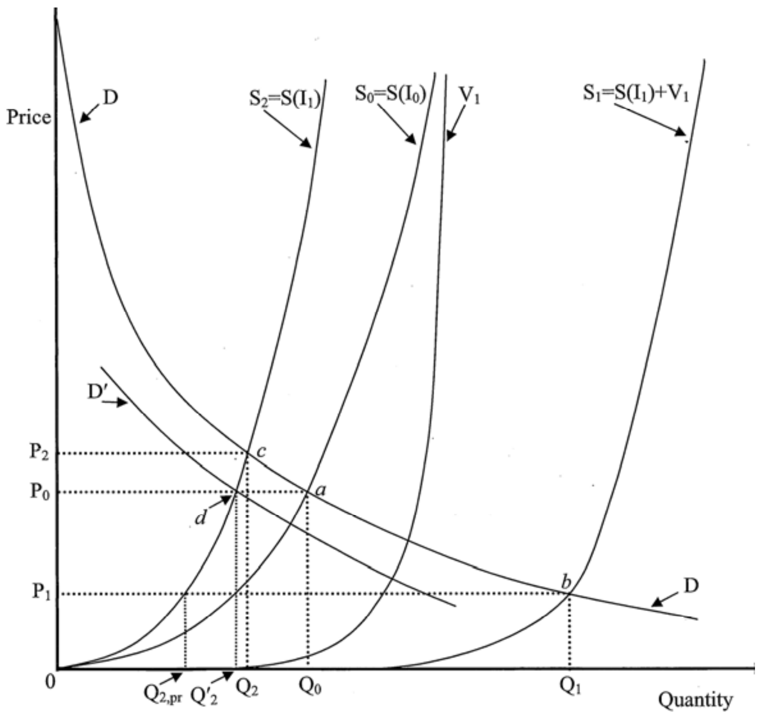

Figure 4.4: Shifts of market demand and supply curve during pre-disturbance, salvage period and post-salvage conditions[7]

[7] (Prestemon & Holmes, 2008).

S_0 is the pre-disturbance supply curve with equilibrium at point a. During the salvage period, two phenomena occur: first, the supply curve shifts back to S_2 due to a smaller inventory $I_1<I_0$, available for harvest. Second, a salvage supply curve, V_1 is introduced in days, months, even years after the storm[8]. Adding S_2 and V_1 moves the supply curve to S_1, with an equilibrium at point b and defines the salvage epoch price, P_1 ($<P_0$) and quantity Q_1 ($>Q_0$). Over time, the salvage curve shifts back towards the vertical axis and eventually disappears. This second epoch lasts several years. During the third epoch, the supply and demand curve are in equilibrium at point c, the price is higher and the quantity is lower than in the pre-disturbance epoch. This epoch lasts until the timber inventories return to pre-disturbance level. In the case of Hurricane Hugo in South Carolina, USA (Prestemon & Holmes, 2000) found a timber price enhancement of about 15% for Southern Pine timber due to inventory reductions, and (Prestemon & Holmes, 2004) concluded that this epoch will last for 23 years[9] for Southern Pine sawtimber.

Similar phenomena of timber and salvage market reactions were also observed after past extreme winter storm occurrences in Baden-Württemberg. Such markets (price changes, inventory losses, etc.) and associated phenomena can be modelled in system dynamics simulations to analyse the impacts of extreme winter storms on forestry over time.

4.3 System dynamics for impact assessment

4.3.1 Components of system dynamics

The main components of system dynamics are stocks and flow diagrams, causal loop diagrams and feedback loops (Figure 4.5).

[8] Depending on when and how much of the salvage timber is brought to the market.

[9] Based on the simulation using empirical price and quantity parameters derived for hurricane Hugo.

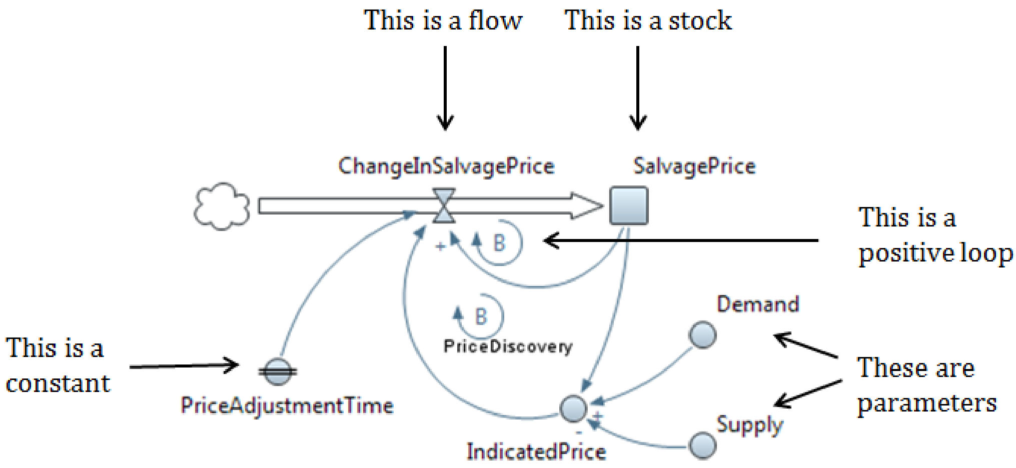

Figure 4.5: A simple system dynamics model including main components

Stocks are used to represent a system's present state, while the flows represent the natural forces that influence the stocks, changing their state over time. A good example of this is a forest growth model where the stock accounts for the timber volume, while growth rate and thinning rate account for the system's flows (Figure 4.6).

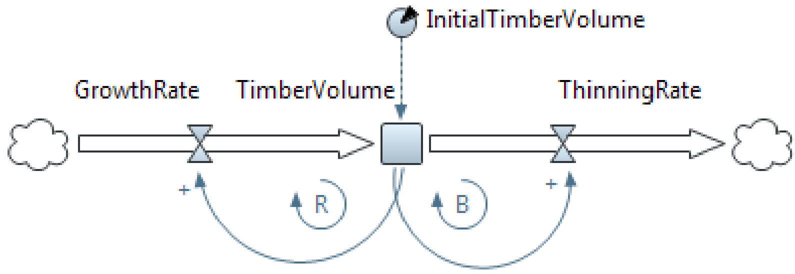

Figure 4.6: A simple forest growth model illustrated with stocks and flows

The number of stocks and flows depend on the modeller's judgment for what is the optimal way to address the dynamics in the system (F. A. Ford, 1999). Dynamic behaviour occurs when flows accumulate in stocks. The stock will increase or decrease depending on which of the flows (inflows/outflows), has a bigger value. For the case where both flows are equal, the system will result in a dynamic equilibrium.

The identification of major stocks is very important in system dynamic models, because they represent the state of the system upon which decisions and actions are based. They are the source of inertia and memory in the system, they create delays and generate disequilibrium dynamics by decoupling rate flows (Sterman, 2000), (Radzicki & Taylor, 1997).

Feedbacks and causal loops are keys to the dynamics seen in stocks and flows. Causal refers to the relationship between cause and effect, while loop is the closed chain of this relationship that generates the feedback. Loops are identified by positive (balancing) and negative (reinforcing) feedback and without any value connotation (Figure 4.6).

The interactions between the loops explain the behaviour of the system. If there are no loops, there is no internal dynamic. Causal loops enable the understanding of the impact of external changes that affect the system. For example, a positive loop will lead to exponential growth, showing the over proportional impact of the outside influence. On the contrary, a negative loop could even wear down the system over time (F. A. Ford, 1999).

System dynamics, compared to other models, e.g., agent based models, is the most suitable to realistically deal with the proposed research problem. In fact, three aspects prove that system dynamics is the most appropriate approach:

- Forestry is a complex system that incorporates different subsystems, e.g., environment, forest management decisions, timber economics, etc. They interact with one another and can be modelled through stocks and flows, as well as feedback structures, which are the core components of system dynamics.
- The interaction of different subsystems and their aggregated outcomes are not linear. The non-linearity can be modelled using system dynamics. For instance, the degradation of salvage quality can be modelled considering different degradation rates throughout the salvage operation period.
- The influence of some of the model parameters does not take place immediately, rather accumulate over time. Such phenomena can be explained by delays in the system dynamics model. For instance, forest owners' decisions on the amount of salvage to be sold in the market can be explained by delays. They can sell certain percentage of the total salvage in the first years, while the remaining salvage can be sold in the following years.

4.3.2 System dynamics in economic modelling

4.3.2.1 Characteristics of economic modelling

System dynamics was originally created as a tool to help managers better understand and control corporate systems. Today it is applied to problems in a wide variety of academic disciplines, including economics where the economists apply system dynamics principles, especially due to the possibility of incorporating non-traditional ideas into formal models (Radzicki, 2011).

Economists prepare economic models to logically isolate and reorganize complicated chains of cause and effects that influence numerous interacting elements in an economy. The models help economists and policy makers to experiment, produce different scenarios and to evaluate the effects of alternative policy options. There are mainly four types of economic models (Evans, 1997):

- Visual models - shown in graphs,
- Mathematical models - shown in equations with exogenous and endogenous variables,
- Empirical models – shown in equations with data originated from case studies or statistics,
- Simulation models - written in computer programmes with feedback and secondary effects included.

Most models used in economics are comparative static models which show what happens over time (or as time passes), but time itself is not represented or embodied directly in the model. However, dynamic models directly incorporate time into their structure. It is usually done considering difference or differential equations. Dynamic models must be simplified so that the difference equations (or especially differential equations) can be solved without difficulty (Evans, 1997).

4.3.2.2 Application of system dynamics models in economics

After the creation of system dynamics in the mid-1950s, a wide range of simulation modelling has been formulated to analyse economics and markets in different fields, e.g., combination of hydrology and economics to model water resources (Ewers, 2005), interaction between economics and environment (O'Regan & Moles, 2006), economic evaluation of sustainable transport (Schade, 2005), sustainable development (Moffatt & Hanley, 2001), global food markets (Kim, 2010), world coffee markets (Osorio & AMBURO, 2009), diffusion models for new technologies (Bosshardt, Ulli-Beer, Gassmann, & Wokaun, 2007), etc. An exemplary list of applications of system dynamics in economics, renewable energy and forestry is given in Figure 4.7.

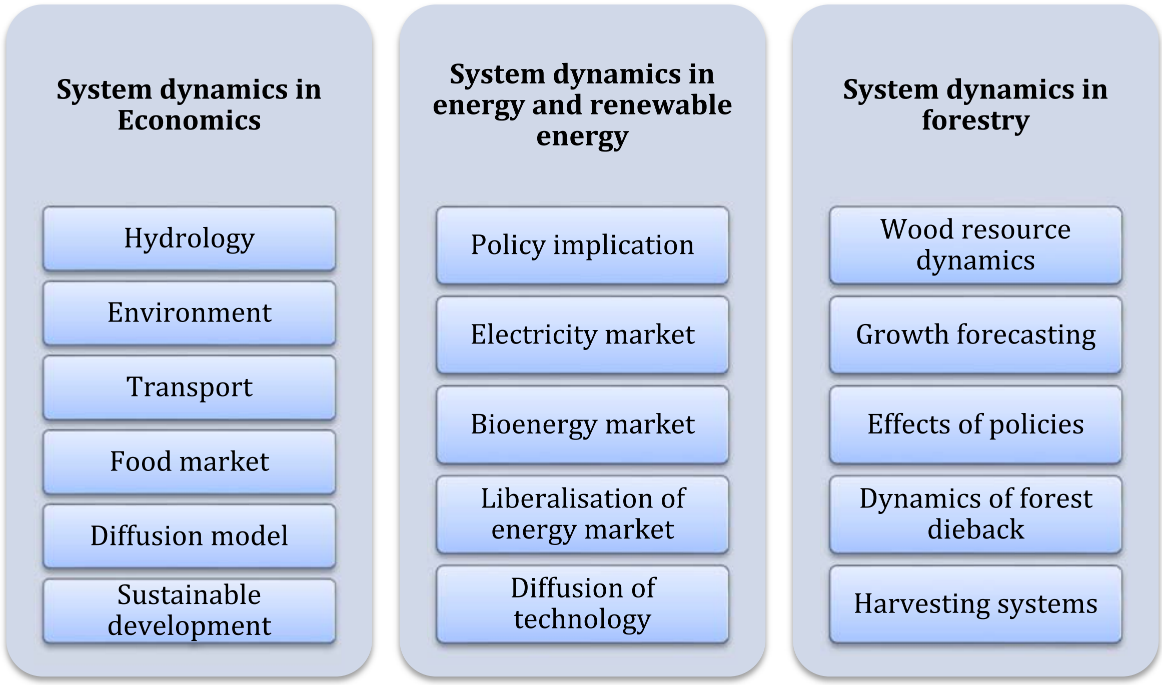

Figure 4.7: Examples of application domains of system dynamics in economics, energy and forestry

The system dynamics method applied in the field of energy and renewable energy cover, e.g., diffusion of technologies (Ben Maalla & Kunsch, 2008), (Peipert, Severyn, Hovmand, & Yadama, 2008), energy related policy implications (Choucri, Goldsmith, & Mezher, 2008), traditional and renewable energy markets (Bartoszczuk, 2006), (Miller & Sterman, 2007), (Franco, Ochoa, & Flórez, 2009), (Rooney, Nuttall, & Kazantzis, 2013), (Sandvik & Moxnes, 2009), (Vogstad, 2004), (Jager, Schmidt, & Karl, 2009; Scheffran, BenDor, Wang, & Hannon, 2007), (Jones, 2009), (Fan, Yang, & Wei, 2007), etc. An extensive literature review on the use of system dynamics models in different energy topics related to strategic planning and policy analysis during the 80s and 90s is given in (Radzicki & Taylor, 1997).

Applications of the system dynamics method in the forestry sector have been less conformist (Buongiorno, 1996). For instance, (Lönnstedt & Randers, 1979) investigated the wood resource dynamics in the Scandinavian forestry sector, and developed a system dynamic simulation model to explain the likely future effects of various policies - no regulation (transition is governed by market forces) and strict regulation - to illustrate how the simulation of Scandinavian forestry can be used for long term policy discussion in the forestry sector. (Schwarzbauer, 1992) studied the growth forecasting in Austrian forests, while (Bossel, 1986) analysed the dynamics of forest dieback and of tree growth under pollution damage affecting leaves and/or feeder roots using two dynamic models of basic tree processes. (McDonagh, 2002) proposed a system dynamic based model of harvesting systems to improve timber harvesting management. Moreover, (Visser et al., 2004) developed a model to simulate different harvesting systems' production efficiency with different stand and terrain parameters. Recently (Collins, de Neufville, Claro, Oliveira, & Pacheco, 2013) used system dynamics to explore how interactions between physical and political systems in forest fire management affect prevention policies in Portugal.

An overview of the use of system dynamics in forest research is illustrated in Table 4.

Table 4: Applications of system dynamics in forest research

Reference	Field of research
(Lönnstedt & Randers, 1979)	wood resource dynamics in the Scandinavian forestry sector and policies
(Schwarzbauer, 1992)	growth forecasting in Austrian forests
(Bossel, 1986)	dynamics of forest dieback and of tree growth under pollution damage
(McDonagh, 2002)	models of harvesting systems to improve timber harvesting management
(Visser et al., 2004)	a model to simulate different harvesting systems' production efficiency
(Collins et al., 2013)	explore how physical-political dynamics affect suppression/prevention policies in forest fire management

On the other hand, several discussions and attempts on integrating input-output (IO) models into system dynamics models have also been carried out (Amsyari, 1992; Braden, 1981; Krallmann, 1980; Moffatt & Hanley, 2001). However, due to the lack of data and complications of IO models' integrations into the system dynamic framework, most of them were not successful.

System dynamics was not yet directly applied in assessing economic impacts of extreme events. A review on other modelling approaches that emerged in recent years is given in Section 1.2.1 and Section 4.1.2.

4.3.3 Combination of GIS and system dynamics

4.3.3.1 Challenges and advantages

In many modelling approaches, spatial dimension has been a key factor to understand and to analyse the spatial pattern of fire and wind damages to forests (Pascual & Guichard, 2005). On the other hand, system dynamics (and other computer simulation methods) have been applied to investigate non-linear social and socio-economic systems with a focus on the understanding and qualitative prediction of a system's behaviour (Schieritz & Milling, 2003). The combination of both GIS and simulation models involves several theoretical and technical challenges (Goodchild, Steyaert, & Parks, 1996; Yates & Bishop, 1998). These are summarized in Figure 4.8.

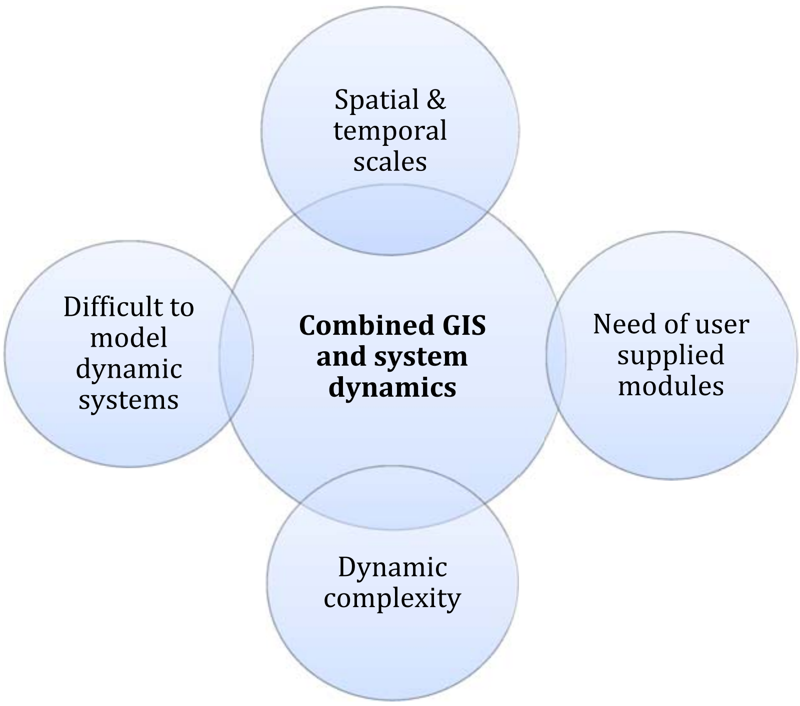

Figure 4.8: Key challenges in a combined spatial and system dynamics approach

For instance, the scaling problem was recognised as a complex issue. (Mazzoleni, Giannino, Colandrea, Nicolazzo, & Massheder, 2003) reviewed several papers discussing the importance of consideration of both spatial and temporal scales. (Despotakis & Giaoutzi, 1996) discussed the missing nodes between the field of GIS modelling and non-spatial system dynamics modelling. They urged the integration of both fields in a dynamic way and provided links in both theoretical and practical sense and concluded that the socio-economic and ecological spatio-temporal phenomena may be efficiently modelled by means of traditional GIS and system dynamics systems, enhanced with user supplied modules, e.g., to change the input parameters, initial values, etc.

(Sterman, 2000) also explained that dynamic complexity arises because natural and human systems are: tightly coupled (components of the system interact with one another), governed by feedback, non-linear, and history dependent (making a particular choice precludes other options and determines the destiny), etc.

However, the combination of GIS and system dynamics in economic modelling brings several advantages (Despotakis, Scholten, & Nijkamp, 1991; Groothedde, 2000; Nyerges, 1991).

- It overcomes the limitations in the individual models: GIS and system dynamics follow different modelling steps and are aimed at solving problems differently, as they are developed for different purposes. Both of them have limited capabilities in modelling and simulation. GIS is a particularly useful medium for representing model input and output of a geospatial nature. However, GIS is not well suited to dynamic modelling. In particular, problems of representing time and change within GIS are identified. Many GIS models are unable to handle a full integration of spatial and dynamic processes (Mazzoleni et al., 2003). On the other hand, simulation methods cannot represent spatial entity and perform geospatial analysis. Therefore, the combined spatial and system dynamic approach helps to overcome individual limitations.
- It allows spatially explicit and dynamic models: System dynamics provides insight into the feedback processes inherent in the evolution of a system. GIS is inherently static but provides spatial databases as well as statistical and visual data interpretation methods. Moreover, economic analysis can help decision makers to understand the causes and consequences of their decisions, as well as to evaluate trade-offs and to set priorities. Economists are generally familiar with dynamic processes operating over time, and less familiar with dynamic processes operating over space (T. P. Holmes, Huggett, & Pye, 2008). Combing the three will make it possible to develop a model that is both dynamic and spatially explicit.
- It allows development of a decision support tool: A spatial decision support system can generate and analyse multiple scenarios of possible management options (Hazelton, Leahy, & Williamson, 1992). (Clark, 1990) described a

conceptual framework for modelling and simulating complex spatial dynamic systems for decision making[10].

Therefore, a combined spatial and system dynamics economic modelling approach offers a single framework for modelling conceptually different models. Such framework would provide the capability to model feedback-based complex dynamic processes in time and space while giving insight into the interaction among different components of the system (Ahmad & Simonovic, 2004).

4.3.3.2 Application of system dynamics models in GIS

Over the last several decades, many studies have discussed the incorporation of spatial issues into system dynamics models (Ahmad & Simonovic, 2004; BenDor & Metcalf, 2006; Deal, Farello, Lancaster, Kompare, & Hannon, 2004; F. A. Ford, 1999; Sanders & Sanders, 2004), but recently techniques have been developed for explicitly representing dynamics as they occur in spatially extended systems (Deal & Schunk, 2004; Scheffran et al., 2007).

(Ahmad & Simonovic, 2004) provided a literature review on the attempt of combining GIS and system dynamics and identified that for spatio-temporal dynamic modelling, the relationship between time and space is not explicit in many cases. A brief overview of the case studies and application is given in Table 5.

Table 5: Overview of applications combining GIS and system dynamics

Reference	Field of research
(Scheffran et al., 2007)	Introducing bioenergy crops
(Xu & Coors, 2012)	Sustainability assessment of urban residential development
(Groothedde, 2000)	Dynamics in spatial logistic chains
(BenDor & Metcalf, 2006)	The spatial dynamics of evasive species spread
(Hovmand & Pitner, 2005)	Combining system dynamics, social networks and GIS
(Ahmad & Simonovic, 2004)	Simulation of Water Resources Systems
(Sancar & Allenstein, 1989)	Planning and design for community development

[10] The framework implements discrete event theory as a method for modelling the temporal system dynamics and cellular automata theory as a method for modelling the spatial system dynamics.

(Scheffran et al., 2007) developed a combined agent based and system dynamics based model to examine the spatial and economic conditions necessary for introducing bioenergy crops into the Illinois landscape. The spatial dynamic model explores the process by which individual farmers optimized profits through crop selection and cost optimization.

A case study to develop an integration of system dynamics and GIS technology for sustainability assessment of urban residential development was proposed by (Xu & Coors, 2012). They developed a tool to inform decision makers on whether residential urban development is sustainable or not. It also provides further information about housing equilibrium.

(Groothedde, 2000) focused on the development of an aggregate spatial system dynamics model for logistics and described different approaches in aggregate freight transportation modelling, system dynamics modelling and the combination of two approaches. A short review of different approaches to incorporate spatial components in system dynamics models is also given.

(BenDor & Metcalf, 2006) developed a spatial dynamic model to capture the behaviour of invasive species spread and tested several policy scenarios. For this reason, parasite-host system dynamics were extended spatially using a spatial modelling environment.

The approach proposed by (Hovmand & Pitner, 2005) brought system dynamics, social network systems and GIS together in a novel way to understand the dynamic relationship between environment and perception of safety and to study complex interactions of multiple non-linear feedback loops.

(Ahmad & Simonovic, 2004) proposed a spatial system dynamics approach with an application to flood management in the Red River basin in Canada. The approach provided the much-needed capability to model feedback-based complex dynamic processes in time and space while giving insight into the interactions among different components of the system. Earlier, (Sancar & Allenstein, 1989) proposed a methodology to make system dynamics modelling more integral in planning and design for community development by including spatial representations.

The literature review helps to identify the key topics that need to be considered in a combined spatial and system dynamics modelling framework. Some researchers were partially successful in combining them, and others discussed the opportunities and/or limitations and were less effective. Moreover, the case studies in different fields justify the applicability in decision support systems and economic modelling.

However, such framework is not yet applied to analyse the economic impacts in forests.

4.4 Conclusion and further research steps

The spatial dimensions of extreme winter storm events vary significantly across a region and the cumulative impact at present and in future is unknown. Many timber dependent industries and other services dependent on forest ecosystems are affected heavily by such events. Various economic factors, e.g., timber and salvage market, demand and supply (elasticities play an important role in the determination of salvage prices), timber management and salvage operation strategies, etc. influence the assessment of impacts. Therefore, by considering these factors, it would be possible to understand how the impact might evolve and to assess the dynamic impacts of extreme winter storms on forests. The theoretical discussion and literature review performed in this chapter serve as the foundation to implement a combined spatial and system dynamics based economic impact model.

For this reason, in **Chapter 5**, the system dynamics modelling approach is formulated considering the state of the art of modelling paradigms. The forestry sector is divided into five submodels (regarding salvage price, salvage value, standing timber value, forest clearing area value, and pre-storm timber value submodel). Then the dynamics of model parameters and associated assumptions of different submodels are illustrated. Subsequently, the data sources required for the reference simulation run and corresponding results of all the submodels are explained and evaluated. Finally, the system dynamic model structure and the results are validated through a set of structural and behavioural tests.

5 Model Formulation and Results

5.1 Modelling approach

5.1.1 Description of submodels

Based on the main research questions and objectives of this study, proposed system dynamics modelling approach is formulated in five submodels (Figure 5.1):

a. Salvage price submodel
b. Salvage value submodel
c. Standing timber value submodel
d. Forest clearing area value submodel
e. Pre-storm timber value submodel

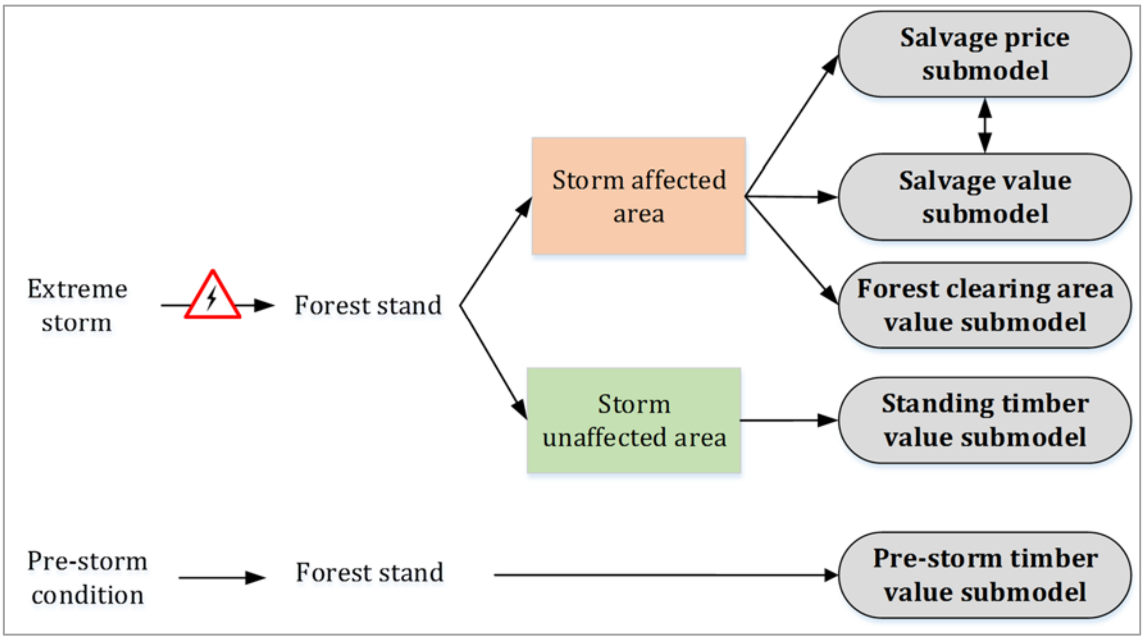

Figure 5.1: Description of the five submodels in a system dynamics modelling approach

The salvage price, salvage value, standing timber value and forest clearing area value submodels explain the post storm conditions in the forest after the extreme storm occurs. The pre-storm timber value submodel illustrates the timber inventory, as well as the price development and timber growth in the past and serves as a reference for projections into the future.

The salvage price submodel is formulated considering the price discovery approach where the market actors do not know the demand and supply curves of the market participants. This submodel is adapted after (Sterman, 2000), who performed a rigorous analysis on the model parameters and their implications and influence on model results. The remaining four submodels are portrayed following the theoretical discussions in Section 2.3.3 and Section 4.2, as well as the forest management best practices observed in the state of Baden-Württemberg.

(Sterman, 2000) emphasized that the time horizon selected should extend far enough into the future to capture the delayed and indirect effects of potential policies. It is evident that the impacts of extreme winter storms last several decades, mainly due to loss of timber and time required to regenerate new trees. The timber and salvage markets can show price changes which last several years (explained in Section 4.2.2).

Therefore, in this study, in order to consider these delayed and indirect effects two different time horizons are selected. Such decision is guided by the overall objective of the research and the recommendations made by foresters. In fact, looking into the characteristics of the problem context, the quality of salvage and its value expires after 5 years as they can neither be used nor sold for any purpose after this period. Therefore, for modelling salvage price and associated salvage values, a time horizon of 5 years is considered. On the other hand, timber growth (in forest clearing areas or unaffected forest areas) can continue even for several decades, but the regenerated trees in forest clearing areas get stability and become economically valuable after 20 years. Moreover, the post storm impacts are observed until this timeframe (see Section 4.2). Therefore, for modelling forest clearing areas and standing timber, a time horizon of 20 years is assumed. Selection of an extended time horizon, e.g., up to 50 years or more would be subject to additional uncertainties in results, compared to the time frame of 20 years.

All submodels are run simultaneously and some of their outputs are dependent on others. For instance, the salvage price submodel - which identifies the annual development of salvage price throughout the simulation run - is used as an input into the salvage value submodel to determine the value of marketable salvage. Moreover, the salvage price submodel is also dependent on the salvage value submodel as it requires annual marketable salvage (reference supply) as an input.

The spatial resolution and temporal extent of these submodels vary as well. For instance, the salvage value submodel runs in each district, whereas the salvage price is calculated for the state of Baden-Württemberg (spatial extent); but the temporal extent of both submodels is 5 years. The other three submodels (i.e., forest clearing area value, standing timber value and pre-storm timber value) are run simultaneously in each district for 20 years. However, all submodels maintain the time step of one year[1], i.e., the model outputs and inputs are plotted against each time step (Table 6).

Table 6: Spatial and temporal characteristics of the five submodels

Condition	Submodel	Spatial resolution	Temporal extent / Time step
After storm	Salvage price	Baden-Württemberg	5 years / yearly
	Salvage value	District	5 years / yearly
	Forest clearing area value	District	20 years / yearly
	Standing timber value	District	20 years / yearly
Pre-storm	Pre-storm timber value	District	20 years / yearly

5.1.2 Model assumptions

Several assumptions are formulated considering the overall objectives of the research and the intended simplicity of the modelling approach.

- The proposed model does not demonstrate the occurrences of another storm during the simulation run, for which the economic impacts might be different. Such phenomena are difficult to model as the uncertainties are increased due to additional complexity in model structure and associated assumptions. In this study, the economic impacts due to a particular stochastic extreme winter storm are evaluated.
- The transport cost of salvage timber and residues to different industries are not considered in assessing the total economic impacts. However, in this research, transport costs of timber and salvage within the forest areas, i.e., from the locations of fallen trees to the nearby forest roads (*Frei Waldstraße*), which is accessible by commercial vehicles, are considered.
- In case of an extreme winter storm, the construction of storage facilities requires additional expenditure and thus it might increase the associated

[1] System dynamics modelling also allows simulation in other time steps, e.g., days, weeks, months, etc. Time step is the incremental change in time for which the governing equations are being solved.

cost. But in Baden-Württemberg, salvage timber is normally either brought to the market immediately after quick logging or it is left in natural state for a short period of time in order to sell at a later period. For this reason, the storage cost of the salvage is not considered in this model.

- Import and export of wood can influence the economic impact. After a storm, the excess salvage wood in one region may be exported to regions where wood deficiencies exist. But such statistic at district level is missing and therefore, for simplicity purpose, both import and export are not considered.
- After an extreme storm, timber and salvage prices may vary across regions. But the difference is negligible as forest offices in Baden-Württemberg are aware of these price variations and they adjust the prices accordingly in order to maintain the regional price balance. Therefore, the geographical variation of price is not relevant for this study.
- Influence of other sectors and technological progress regarding harvesting methods or salvage operation are assumed as at current state. So, they will not influence the model results.

5.1.3 Model boundary chart

The model boundary chart of the proposed research can be illustrated by identifying the endogenous and exogenous variables[2]. These variables as well as the excluded variables help to depict the scope and structure of the model. Figure 5.2 describes the model boundary chart.

[2] Endogenous variables are determined within the model. Their values become known when the model has been run. Exogenous variables come from outside of model and their values are pre-set (Evans, 1997).

Exogenous variable	Endogenous parameter	Excluded
Initial salvage price	Salvage price	Price variation
Reference demand	Indicated price	Market size
Elascity of demand and supply	Reference supply	Fuel or energy price
Salvage operation cost	Supply and demand	Import-export of timber
Standing timber volume	Salvage value	Wood flows
Pre-storm timber volume	Timber growth rate	Non-market values
Price adjustment time	Timber thinning rate	Etc.
Discount rate	Forest clearing area value	
Salvage degradation	Standing timber value	
Etc.	Pre-storm timber value	
	Etc.	

Figure 5.2: Description of the model boundary chart

5.1.4 Subsystem diagram

A subsystem diagram shows the overall architecture of a model (Sterman, 2000). The proposed system dynamics modelling approach is formulated in five submodels, therefore, the relations and dependences of these submodels are represented through the subsystem diagram (Figure 5.3). A detailed description of each submodel with the stock and flows diagram is given in Section 5.3.

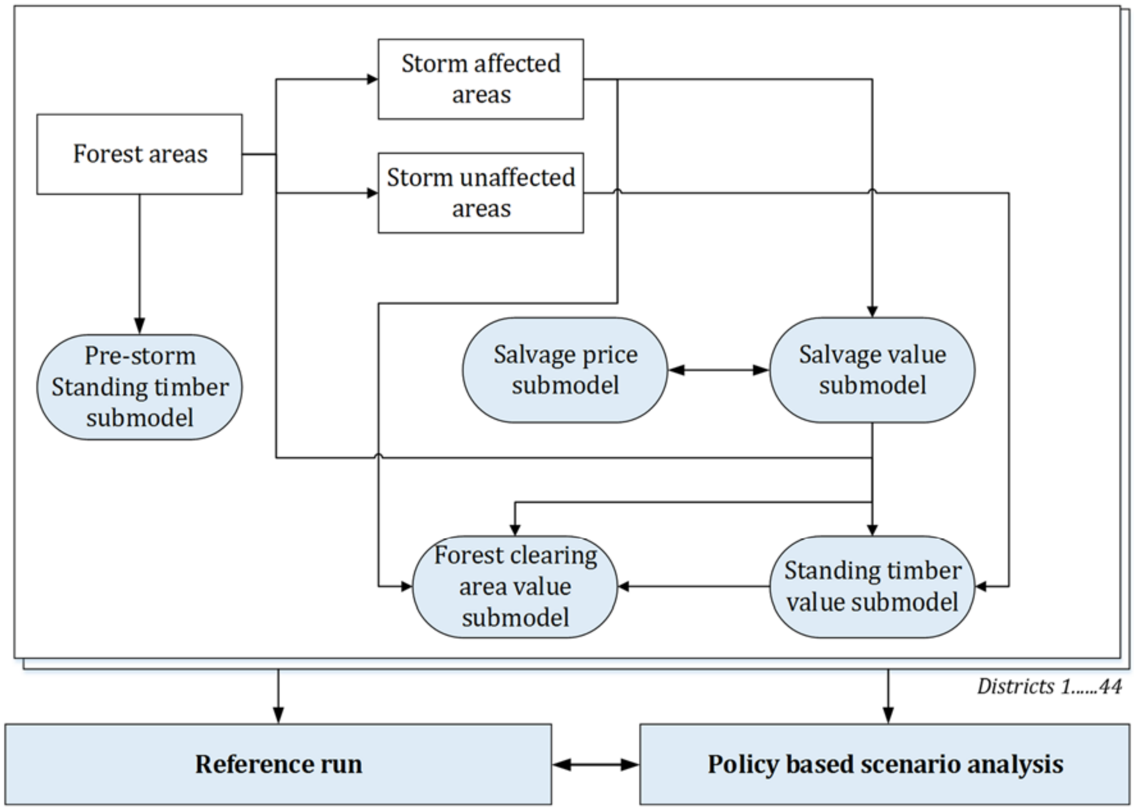

Figure 5.3: Subsystem diagram of the system dynamics model

5.1.5 Causal loop diagram and feedback loops

A causal loop diagram emphasizes the feedback structure of the problem to be investigated (Sterman, 2000). The important feedback loops are also identified. The proposed model is represented as a causal loop diagram to show the causal relationships among the five submodels. The causal links among variables are denoted with arrows from a cause to an effect. Some of the most important loops and causal influences of the model are illustrated in (Figure 5.4).

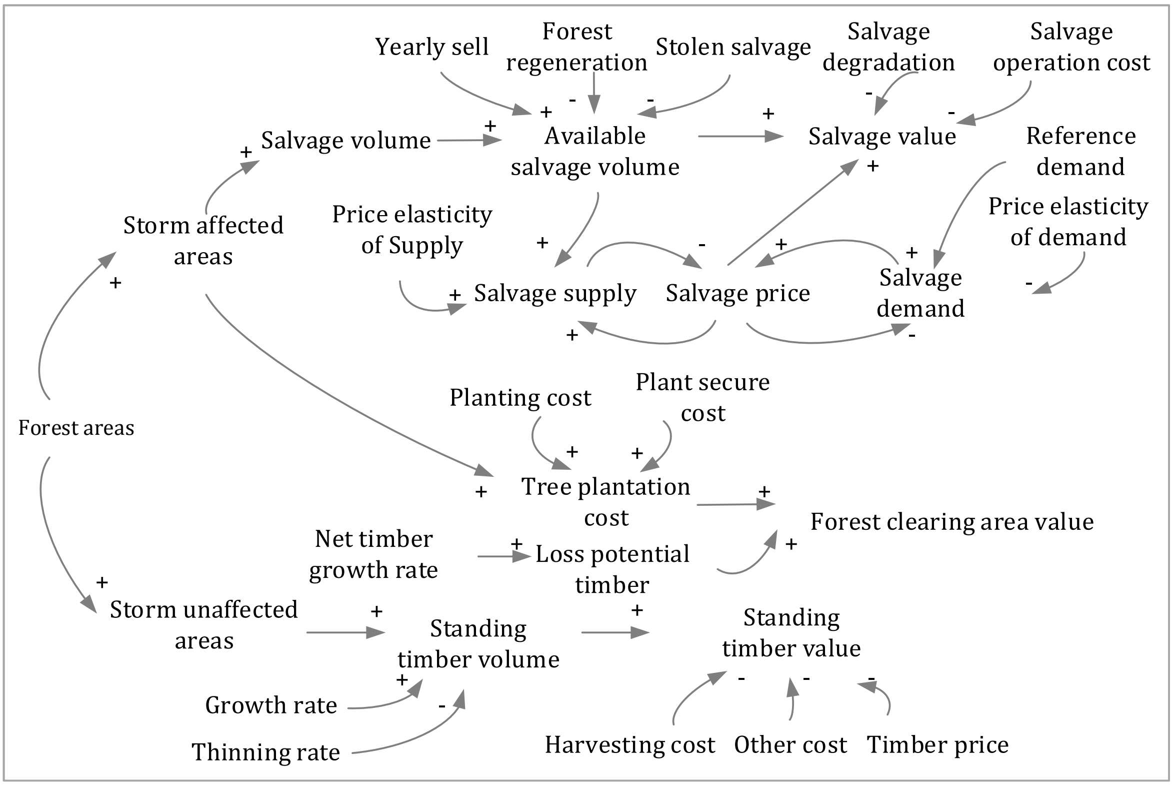

Figure 5.4: Causal loop diagram of the system dynamics model

Loop identifiers show whether the loop is positive (reinforcing) or negative (balancing). 11 feedback loops are identified in the five submodels (Table 7). A detailed illustration of these loops is given in the stock and flow diagrams (Section 5.3).

Table 7: Identification of different loops within the model

Submodel	Loops	Type of loops
Salvage price and salvage value	L1: Price adjustment	Balancing
	L2: Price discovery	Reinforcing
	L3: Demand response	Balancing
	L4: Supply response	Balancing
	L5: Salvage availability	Balancing
Forest clearing area value	L6: Loss of potential timber	Reinforcing

Standing timber value	L7: Standing timber growth	Balancing
	L8: Standing timber cut	Reinforcing
Pre-storm timber value	L9: Timber price discovery	Balancing
	L10: Timber growth	Reinforcing
	L11: Timber cut	Balancing

5.2 Model parameter and stock and flow diagram

5.2.1 Overview of parameters

Several factors influence the assessment of economic impacts of winter storms. They are formulated based on the forest management best practices observed in the state of Baden-Württemberg as well as considering the literature reviews (Chapter 4). Some parameters are independent of submodels and are identified as global. These are forest areas, storm affected areas, forest growing stock (used to convert area to volume) and discount rates.

A description of all these model parameters and related data sources is given in Section 2.3.4. The non-global parameters are outlined in Table 8.

Table 8: Overview of the model parameters in different submodels

Submodels	**Model parameters**
Salvage price	Initial salvage price Reference price Reference demand Reference supply Demand elasticity Supply elasticity Sensitivity of price to demand supply balance Price adjustment time
Salvage value	Forest regeneration percentage Stolen salvage percentage Sell percentage Salvage degradation factor

	Logging cost Other cost
Forest clearing area value	Planting cost Plant secure cost Net timber growth rate
Standing timber value	Fractional growth rate Fractional thinning rate Timber price Harvesting cost Other cost
Pre-storm timber value	Fractional growth rate Fractional thinning rate Harvesting cost Other cost Timber price Supply effect on price Time to adjust price

All these parameters can be explained using a stock and flow diagram. It is prepared according to the subsystem diagram and the causal loops explained in Section 5.2.4 and Section 5.2.5, respectively.

The dimensional accuracy of the variables and their units are inspected carefully and several testing runs are performed using the system dynamic framework built within the AnyLogic[3] software (AnyLogic, 2016). An overview of all these variables, parameters and their units is given in Appendix 5.

5.2.2 Salvage price submodel

The salvage price submodel discovers the salvage price in a post-storm market through the analysis of price setting. The price setting can be defined by a price discovery process which determines the price of an asset in the market place through the interaction of buyers and suppliers. Price setting offers one of the most difficult formulation challenges in economic modelling (Sterman, 2000). Prices of

[3] AnyLogic Software allows connectivity with databases and provides a framework for simulating using system dynamics, etc.

some goods and services are very stable, while others change often. There are also different price setting situations. For instance, timber owners respond to supply and demand shocks by either holding timber off the market (in anticipation of higher prices) or offering it up for sale (in anticipation of falling prices). The rational expectations model assures that following an unpredictable catastrophic event, agents of timber supply and demand take account of the new information and prices adjust to a new equilibrium that equates supply and demand (Berck, 1979).

Price formation is an adaptive process in which agents adjust their expectations of prices based on a limited amount of information prior to their decisions. In well-behaving, double-auction markets[4], prices normally converge towards the equilibrium price as predicted by neoclassical economic theory - if exogenous factors are kept constant throughout this process. Price is modelled as a level that adjusts up or down for each time step, proportional to the fractional discrepancy (or difference) between demand and supply, where the time constant (i.e., adjustment time) represents the average time to clear the market (Sterman, 2000). Both the supply and demand sides respond due to the price elasticity and settle at a new price level. This process of continuous adjustment to a changing goal (demand) can be recognised as a simple search process referred to as a hill-climbing search (Sterman, 2000) and is illustrated in (Figure 5.5). This price discovery model, and other modified versions of this model were adapted to a variety of markets - e.g., the paper industry (Taylor, 1999), the chemical market (Homer, 1996), the formulation of interest rate (Hines, 1987) - with generally good results.

[4] A double auction is a real world, do-it yourself market procedure in which participants may make public offers both to buy ('bids') and to sell ('asks'). The item is sold to the highest bidder (Friedman, 1984).

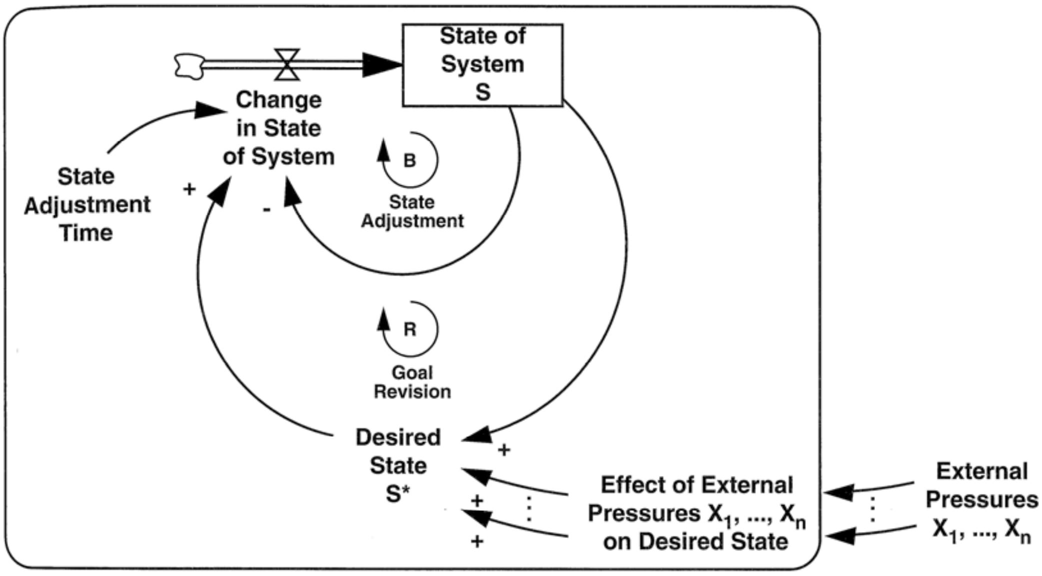

Figure 5.5 Structure of hill-climbing search[5]

This generic price setting formulation proposed by (Sterman, 2000), has been adapted in this research to analyse and explain the salvage price submodel. The hill-climbing structure of the salvage market is interpreted as a continuous search to minimise the discrepancy between demand and supply, while keeping the price level as a decision variable.

The initial salvage price and reference price are given as input in the price formulation submodel. The initial salvage price and reference price for the model are assumed to be the same as with the pre-storm timber price. Then during the simulation - based on the demand, supply and their elasticities, price adjustment time (PAT), as well as other model input parameters - the final salvage price for different years will be determined.

Reference demand and supply of salvage is used as input within the model, from which an annual demand and supply of salvage is calculated. The reference demand - which is calculated based on the annual timber cut and the percentage of wood originated from forests in Baden-Württemberg - is assumed to be the same for each model year. Based on the discussion and statistical evidence (Section 2.3.4), an annual reference demand of 7 million m^3 of raw wood is assumed in this model.

[5] (Sterman, 2000).

The reference supply – which is basically the available marketable timber after the winter storm - is calculated within the salvage value submodel by aggregating the total volume of windthrow trees in all the districts in Baden-Württemberg.

The sensitivity of price to the demand supply balance could be estimated from the data, relating price changes to the relative size of buy and sell orders in the salvage market (Sterman, 2000). Since such data is not available, the sensitivity of price to the demand supply balance is assumed to be 1 meaning that this variable will not have impact on the model[6].

The forestry office confirms that the timber and salvage prices do not change quickly. The price adjustment mechanism and the search process (see Figure 5.5) of salvage price can cause significant time lags that can affect the dynamic behaviour of the model. Therefore, the salvage market shows sluggish price adjustment and so the price adjustment time (PAT) is set to 1 year. Moreover, sensitivity analysis of PAT - with a variation from a minimum of 3 months to a maximum of 1.5 years - will also be performed to evaluate its impact on the salvage price.

Based on these exogenously given input parameters, e.g., initial salvage price, demand supply elasticities, etc. the final salvage price is determined endogenously. The stock and flow diagram (Figure 5.6) of the salvage price submodel is, therefore, prepared after the price discovery of the hill-climbing search model proposed by (Sterman, 2000). The underlying equations (5.1 – 5.7) describe the dynamic development of salvage price.

[6] The sensitivity of price to the demand supply balance will influence system's stability once the value is varied dramatically (Pierson & Sterman, 2013). Since the empirical data is not available for Baden-Württemberg, such assumption is in line with other studies as explained in (Sterman, 2000).

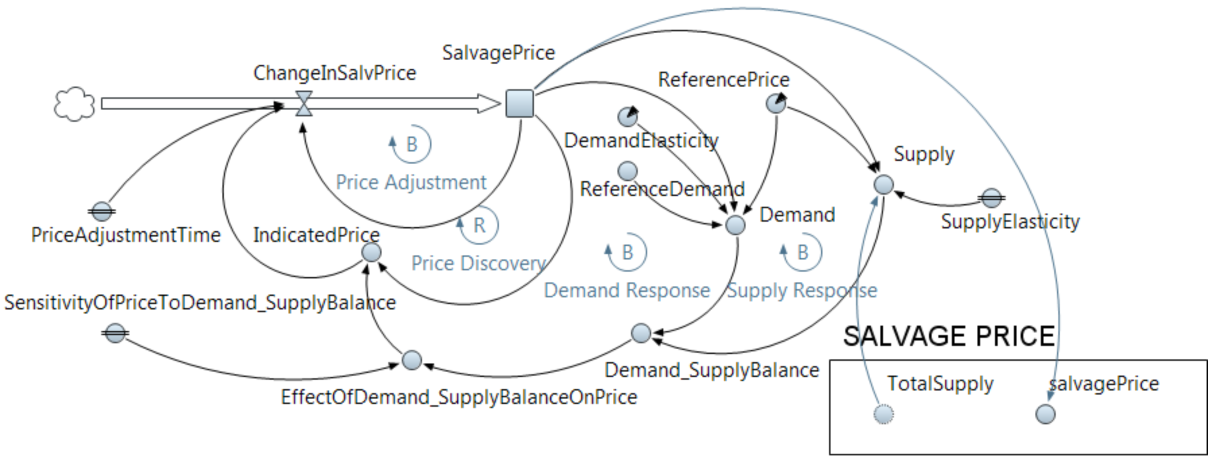

Figure 5.6: Stock and flow diagram of the salvage price submodel

The initial salvage price (P_{sl}) adjusts to an indicated price (IP_{sl}) over an integral given by the price adjustment time (PAT).

P_{sl} [t+1] = P_{sl} [t] + $\int P_{slch}$ [t + 1].dt 5.1

P_{slch} [t +1] = (IP_{sl} – P_{sl})/PAT 5.2

where, P_{slch} is the change in salvage price. The market clearing equilibrium price is unknown and therefore, the market makers form an indicated price (IP_{sl}) based on the current reference price (P_{ref}) and then adjusting it in response to the perceived balance (DS) between demand (D_{sl}) and supply (S_{sl}).

DS = D_{sl} / S_{sl} 5.3

If demand of salvage (D_{sl}) exceeds supply (S_{sl}), the indicated price (IP_{sl}) will rise and so will the actual salvage price (P_{sl}). Therefore, the price will grow exponentially as long as demand exceeds supply. The price will fall as long as supply exceeds demand. The effect of demand supply balance (EDS) on price can be approximated simply by:

EDS = $(D_{sl} / S_{sl})^{sen}$ 5.4

where, ^{sen} > 0 is the sensitivity of price to the demand supply balance. And the indicate price (IP_{sl}) is then formulated as the salvage price (P_{sl}) multiplied by EDS:

IP_{sl} = P_{sl} * EDS 5.5

Earlier in the model, in order to find the market clearing salvage price (P_{sl}), it is assumed that the demand and supply respond to price with constant elasticities. The demand (D_{sl}) and supply (S_{sl}) are determined endogenously considering the reference demand (D_{ref}), reference supply (V_{yasl}) and their elasticities, as well as reference salvage price (P_{ref}) and market clearing salvage price (P_{sl}):

$$D_{sl} = D_{ref} * (P_{sl} / P_{ref})^{ed} \quad 5.6$$

$$S_{sl} = V_{yasl} * (P_{sl}/P_{ref})^{es} \quad 5.7$$

where $^{ed} < 0$ and $^{es} > 0$ are elasticities of demand and supply, respectively.

Some important properties of the salvage price submodel are[7]:

- Salvage equilibrium price [P_{sl}] depends on the demand and supply curve, which are basically defined by the elasticities and reference values,
- The price adjustment time [PAT] and sensitivity of price to the demand supply balance [^{sen}] characterize the disequilibrium behaviour of market makers and do not affect equilibrium price,
- The price formation process forms two loops: (a) price adjusts to the indicated level, forming the negative price adjustment loop, (b) but the indicated price is based on the current price, forming the positive price discovery loop,
- The responses of demand and supply to price form two additional negative loops - (a) demand response and (b) supply response loops, respectively.

5.2.3 Salvage value submodel

The salvage value submodel dynamically determines the net value of salvage in every district in Baden-Württemberg for different simulation years. For this reason, the marketable amount of salvage and the associated salvage price need to be defined. The marketable salvage volume in every district is determined in this submodel, whereas the salvage price is calculated from the salvage price submodel.

Several calculation steps are performed to estimate the marketable salvage. At first, total salvage volume in each district is calculated based on the vulnerability analysis carried out as explained in Chapter 3 including assumptions, e.g., total affected and unaffected areas and the growing stock (area to volume conversion factor) as described in Section 2.3.4. Later, the marketable salvage for the first five years is calculated by subtracting the salvage stolen and the salvage to be kept for regeneration purposes.

[7] They are adapted after the hill climbing search method of (Sterman, 2000).

The decision on annual selling percentages is also considered. This way, the total marketable salvage (or reference supply) in each simulation year is calculated for the whole state. The decision on the time delay regarding the salvage operation or sale plays an important role for the total economic impact. Moreover, the degradation of salvage (which reduces the quality of the timber) and increasing salvage operation cost pose a negative impact on the total salvage value. All these parameters and their values are discussed in Section 2.3.4. The stock and flow diagram (Figure 5.7) and the equations (5.8 – 5.14) describe this submodel.

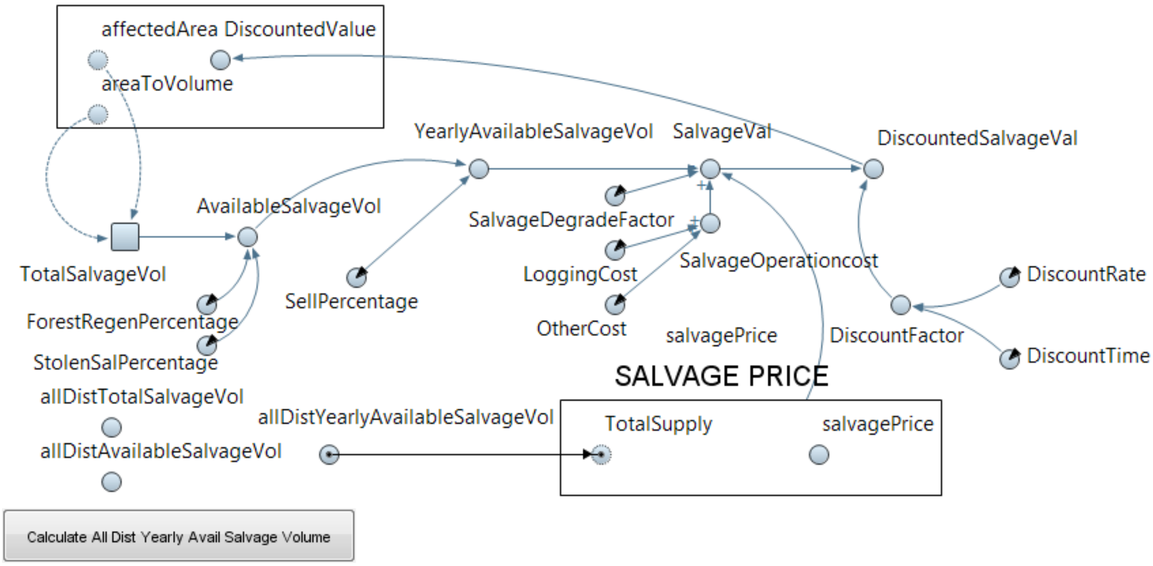

Figure 5.7: Stock and flow diagram of the salvage value submodel

The available salvage volume (V_{asl}) is calculated from the total salvage volume (V_{tsl}), the percentage of salvage stolen (st) and the salvage to be kept in the forest for regeneration (re). The total salvage volume (V_{tsl}) available in each district is calculated by multiplying the total area affected by an extreme storm (A_{af}) with the area to volume conversion factor (av).

$$V_{asl} = V_{tsl} * st * re \quad 5.8$$

$$V_{tsl} = A_{af} * av \quad 5.9$$

By applying the amount of salvage to be sold each year (se), the yearly available salvage volume (V_{yasl}) can be calculated.

$$V_{yasl} = V_{asl} * se \quad 5.10$$

Net salvage value (VA_{sl}) is calculated by deducting the operation costs from the salvage value.

$VA_{sl} = (V_{yasl} * df * P_{sl}) - (V_{yasl} * df * OC_{sl})$ 5.11

$OC_{sl} = C_l + C_o$ 5.12

where, df is degradation factor, OC_{sl} is salvage operation costs, which is the sum of logging costs (C_l) and other costs (C_o). Psl is the input from the salvage price submodel.

The discounted salvage value (DVA_{sl}) is calculated by multiplying the salvage value (VA_{sl}) with the discount factor (df):

$DVA_{sl} = VA_{sl} * df$ 5.13

$df = 1/(1+dr)^{dt}$ 5.14

where, dt and dr are discount time and rate, respectively.

Finally, the sum of the annual available salvage volume in all districts is calculated, which is used as reference supply in the salvage value submodel.

5.2.4 Forest clearing area value submodel

The forest clearing area value submodel dynamically evaluates the costs associated with newly planted trees and potential loss of future timber value (trees would have continued to grow in case no storms would have occurred). The different parameters and related assumptions of this submodel, as discussed in Section 2.3.4, are listed in the equations (5.15 – 5.19) and the stocks and flow diagram (Figure 5.8).

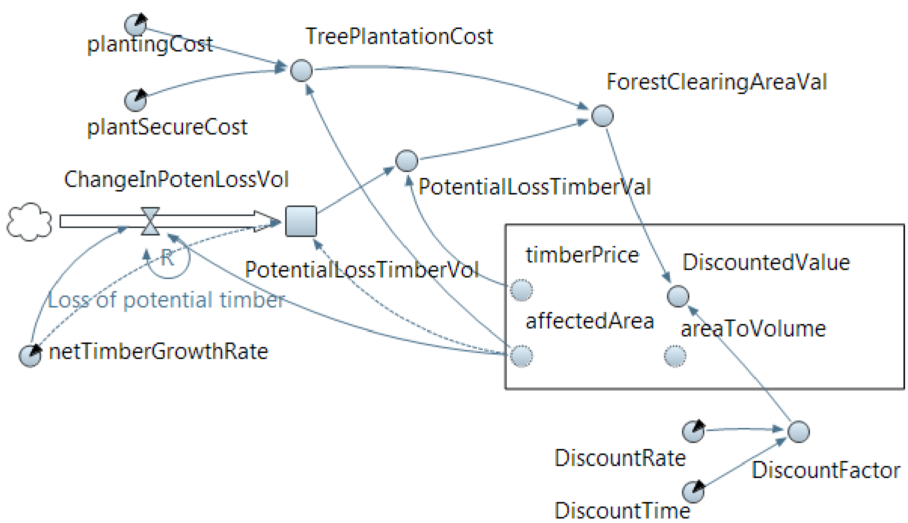

Figure 5.8: Stock and flow diagram of the forest clearing area value submodel

Tree plantation cost (C_{tp}) is calculated as the sum of planting cost ($C_p * A_{af}$) and plant secure cost ($C_s * A_{af}$).

$$C_{tp} = C_p * A_{af} + C_s * A_{af} \qquad 5.15$$

The value of potential loss timber (VA_{lt}) is calculated by multiplying the volume of potential loss timber (V_{lt}) with the timber price (T_p).

$$VA_{lt} = V_{lt} * T_p \qquad 5.16$$

The value of the total forest clearing area (VA_{fca}) is calculated by summing up the C_{tp} and VA_{lt}. Then the discounted forest clearing area value is calculated similarly to the salvage value submodel.

$$VA_{fca} = C_{tp} + VA_{lt} \qquad 5.17$$

The potential loss of timber volume (V_{lt}) is calculated by the initial loss volume over the integral of change in potential timber loss (V_{clt}), which is calculated by multiplying the affected area (A_{af}) with the net timber growth rate (ngr).

$$V_{lt}\,[t+1] = V_{lt}\,[t] + \int V_{clt}\,(t+1).dt \qquad 5.18$$

$$V_{clt}\,[t+1] = A_{af} * ngr \qquad 5.19$$

5.2.5 Standing timber value submodel

The standing timber value submodel dynamically calculates the total value of standing timber within the unaffected storm areas in each district. The standing timber value does not impose additional cost on the economic impact of winter storms, rather it is required to compare with other submodels e.g., pre-storm timber value in order to evaluate the net impacts (see Section 5.4.7).

For this reason, the parameters discussed in Section 2.3.4 are considered as a basis to formulate the dynamic flow and other equations (5.20 – 5.24), which determine the timber volume, timber value, etc. for different years within the stock and flow diagram (Figure 5.9).

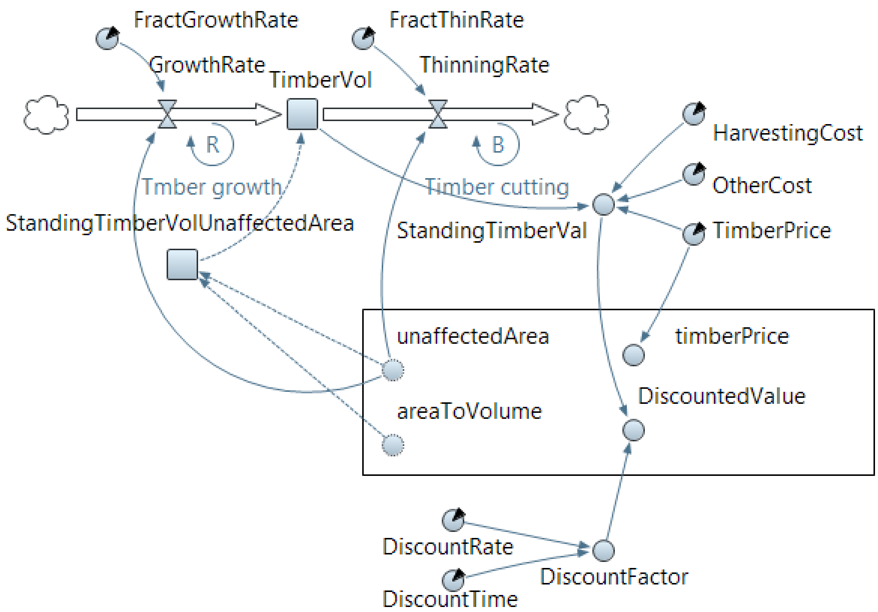

Figure 5.9: Stock and flow diagram of the standing timber value submodel

At first, the volume of the standing timber (V_{st}) is calculated by multiplying the area unaffected by the storm (A_{uaf}) with the area to volume conversion factor (av).

$$V_{st} = A_{uaf} * av \qquad 5.20$$

The timber volume (V_t) is calculated by the initial standing timber volume (V_{st}), over the integral of change in growth rate (gr) and thinning rate (tr).

$$V_t\,[t+1] = V_{st}\,[t] + \int (gr - tr).dt \qquad 5.21$$

$$gr = fgr * A_{uaf} \qquad 5.22$$

$$tr = ftr * A_{uaf} \qquad 5.23$$

where, A_{uaf} is the unaffected area, fgr and ftr are the fractional growth rates and fractional thinning rates, respectively. Finally, the net value of the standing timber (VA_{st}) is calculated by subtracting the harvesting and other costs from the value of the timber ($V_T * P_t$).

$$VA_{st} = (V_t * P_t) - (V_t * C_h) - (V_t * C_o) \qquad 5.24$$

where P_t and V_t are price and volume of the timber, C_h and C_o are harvesting cost and operation cost. Finally, similar to other submodels, the forest clearing area value is discounted to present values.

5.2.6 Pre-storm timber value submodel

The pre-storm timber value submodel evaluates the development of standing timber values in all the districts in Baden-Württemberg without the occurrence of a storm event. The definitions and assumptions of most of the parameters in this submodel, e.g., fractional growth rate, fractional thinning rate, timber price, harvesting cost, and other costs were previously discussed.

This submodel resembles the modelling of the pre-storm situation and is used as a reference condition to determine the value of timber. It ensures a comparative analysis between the pre-storm and post-storm events. A simple dynamic timber price model is developed after (Sterman, 2000), and the parameters and related assumptions used in this submodel are formulated following the descriptions in other submodels. The dynamic equations (5.25 – 5.33) and the stock and flow diagram are described in Figure 5.10.

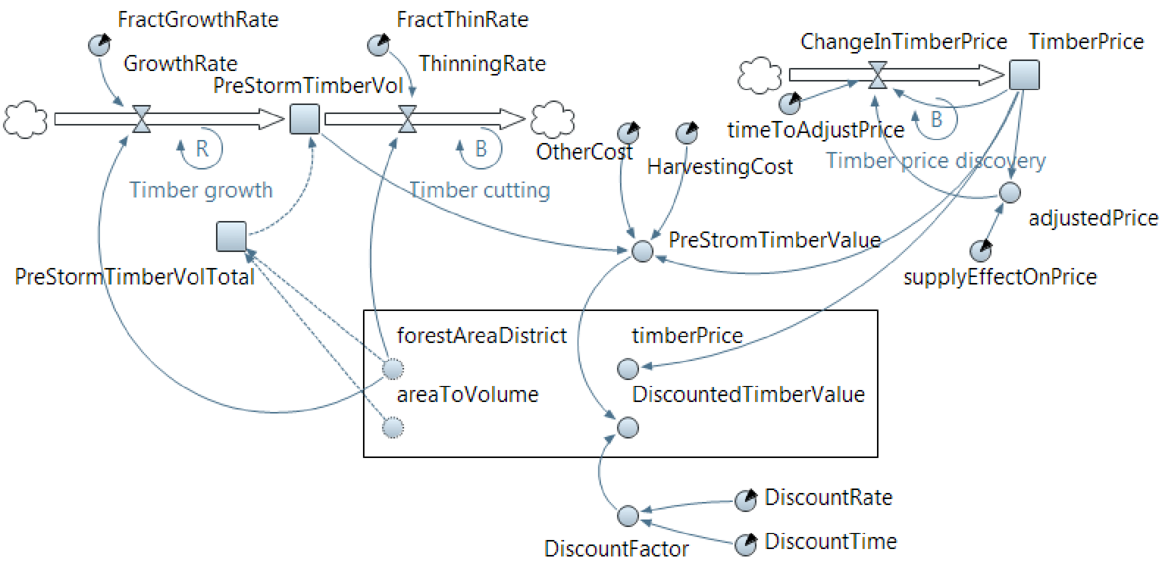

Figure 5.10: Stock and flow diagram of the pre-storm timber value submodel

Total pre-storm timber volume is calculated by multiplying the forested area with the area to volume conversion factor (av).

$VT_{pt} = A_f * av$ 5.25

The yearly pre-storm timber volume (V_{pt}) is calculated by initial timber volume (VT_{pt}), over the integral of change in growth rate (gr), and thinning rate (tr).

$V_{pt}[t+1] = VT_{pt}[t] + \int (gr - tr).dt$ 5.26

$$gr = fgr * A_f \quad 5.27$$

$$tr = ftr * A_f \quad 5.28$$

where, A_f, fgr, ftr are forested area, fractional growth rate and fractional thinning rate, respectively. The pre-storm net timber value (VA_{pt}) is calculated by substracting the timber harvesting and operation cost from the timber value.

$$VA_{pt} = (V_{pt} * P_t) - (V_{pt} * C_h) - (V_{pt} * C_o) \quad 5.29$$

where, P_t, C_h and C_o are timber price, timber harvesting and operation cost, respectively. Similar to the salvage price submodel, a more simplified timber price model is formulated. The timber price (P_{pt}) adjusts to a price (P_{pa}) over an integral given by the time to adjust the price (PAT). The adjusted price is influenced by the supply effect on the price (se).

$$P_{pt}[t+1] = P_{pt}[t] + \int P_{pct}[t+1] .dt \quad 5.30$$

$$P_{pct}[t+1] = (P_{pa} - P_{pt})/PAT \quad 5.31$$

$$P_{pa} = P_{pt} * se \quad 5.32$$

The net timber value (VA_{pt}) is calculated by subtracting the harvesting and other cost from the timber value.

$$VA_{pt} = (V_{pt} * P_{pt}) - (V_{pt} * C_h) - (V_{pt} * C_o) \quad 5.33$$

where, P_{pt} and V_{pt} are price and volume of pre-storm timber, and C_h and C_o are harvesting cost and operation cost. Finally, the discounted timber value is calculated considering the discount rate similar to the other four submodels.

5.3 Reference simulation run and result

5.3.1 Simulation approach

The purpose of the reference simulation run is to understand the model and to build confidence as part of the validation process (Barlas, 1996). In this section, some results of the reference simulation runs are described to illustrate the model behaviour and to identify how it can be used to test the response to new policies. The outputs aim to promote an understanding of the dynamic properties of the multidimensional and interdisciplinary aspects of the model - where different districts accommodate varying forest resources and are impacted differently by the stochastic storm, each of them having unique characteristics. The subsequent runs explained in Chapter 6 also show the responses to various policies.

The simulation results of each of the submodels can be analysed at different geographic and temporal extents, depending on the requirements of the decision makers. For example, they can be evaluated for all districts in Baden-Württemberg or for one or some particular highly vulnerable districts, throughout the simulation years or in a specific year. However, the interpretation of the outcome of all submodels and final results in all the 44 districts is difficult to illustrate, using graphs. Therefore, some highly vulnerable districts are chosen to illustrate the submodels' output. For example, the district of Schwarzwald-Baar-Kreis[8] is highly vulnerable to future extreme winter storms and, therefore, is chosen as a representative district to illustrate the simulation runs. Furthermore, the sensitivity analysis with some of the most important parameters and two policy based scenario analyses is also discussed for the district of Schwarzwald-Baar-Kreis and for Breisgau-Hochschwarzwald as well. The aggregated outcomes of different submodels - for each of the districts in Baden-Württemberg at various simulation years - are also visualized in graphs and maps.

5.3.2 Data sources

The reference simulation run is based on a set of assumptions, definitions and a literature review regarding different model parameters, which are presented in Section 2.3.4; the stock and flow diagram (and the equations) are described in Section 5.3. A summary of these reference values, as well as the related units and corresponding sources is given in Table 9.

[8] In this district, the WofE model predicted a high damage probability, but very low proportions (< 1%) of total forests were actually damaged during the storm Lothar.

Table 9: List of the model parameters and values for the reference simulation run

Submodel	Model parameter	Reference value	Unit	Source
Global	Forest area	differs in districts	ha	WofE model
	Low vulnerable area	differs in districts	ha	WofE model
	Medium vulnerable area	differs in districts	ha	WofE model
	High vulnerable area	differs in districts	ha	WofE model
	Area to volume	377	m^3/ha	Statistics, NFI 3
	Discount rate	4.35	%/year	Expert, Literature
	Discount time	5 and 20	year	Model asuumption
Salvage price	Initial Salvage price	55	Euro/m^3	Literature
	Reference price	55	Euro/m^3	Literature
	Reference demand (Baden-Württemberg)	7000000	m^3/year	Literature, Statistics
	Reference supply (Baden-Württemberg)	model outcome	m^3/year	Submodel output
	Demand elasticity	- 0.5	-	Literature
	Supply elasticity	0.8	-	Literature
	Sensitivity of price to demand supply balance	1	-	Assumption
	Price adjustment time	1	year	Expert
Salvage value	Forest regeneration	20	%	Expert
	Stolen salvage	2	%	Expert
	Sell percentage (1st to 5th year)	[50, 20, 10, 10, 10]	%	Assumption
	Salvage degradation factor (1st to 5th year)	[0.99, 0.89, 0.59, 0.22, 0]	-	Expert, Literature
	Logging cost	7	Euro/m^3	Forest data
	Other cost	2	Euro/m^3	Forest data
Forest clearing area value	Planting cost (first year only)	15000	Euro/ha	Forest data
	Plant secure cost (first 5 years)	1000	Euro/ha/year	Forest data
	Net timber growth rate	0.68	m^3/ha/year	Literature
Standing timber value	Fractional growth rate	12.29	m^3/ha/year	Literature
	Fractional thinning rate	11.61	m^3/ha/year	Literature
	Timber price	differs in years	Euro/m^3	Literature
	Harvesting cost	20	Euro/m^3	Forest data
	Other cost	2	Euro/m^3	Forest data
Pre-storm timber value	Fractional growth rate	12.29	m^3/ha/year	Literature
	Fractional thinning rate	11.61	m^3/ha/year	Literature
	Harvesting cost	20	Euro/m^3	Forest data
	Other cost	2	Euro/m^3	Forest data
	Timber price	differs in years	Euro/m^3	Literature
	Supply effect on price	1	-	Assumption
	Time to adjust price	1	year	Assumption

5.3.3 Salvage price submodel

The salvage price submodel is run for the whole state of Baden-Württemberg and it is assumed that the salvage price does not vary across districts. The salvage price in the first five years is determined based on the initial reference salvage price, the reference supply and demand, and the elasticities of demand and supply. The supply and reference supply of salvage are assumed the same in the first year, but due to varying price elasticities of demand and supply, the modelled supply changes significantly compared to the reference supply. The reference demand is assumed fixed throughout the model run, but the demand also changes due to the price elasticity and other factors.

The reference supply (or the total supply) is the total salvage ready to be sold in the market. Based on the WofE model outcome and model assumptions described in this chapter, theoretically about 176 million m^3 of salvage becomes available in Baden-Württemberg after a stochastic extreme winter storm. After subtracting the amount of salvage to be left out in the forest and the stolen salvage, about 138 million m^3 of salvage is ready to be sold in the market within the next five years. For example, the reference supply in the first three years is 69, 28 and 28 million m^3 and the model supply is 69, 14 and 12 million m^3, which is calculated based on the reference supply, salvage price and supply elasticity. Similarly, the demand in Baden-Württemberg for each model year is calculated based on the reference demand (7 million m^3), salvage price and demand elasticity. In the first three years, the demand is approximately 7, 10 and 11 million m^3, respectively (Figure 5.11, left).

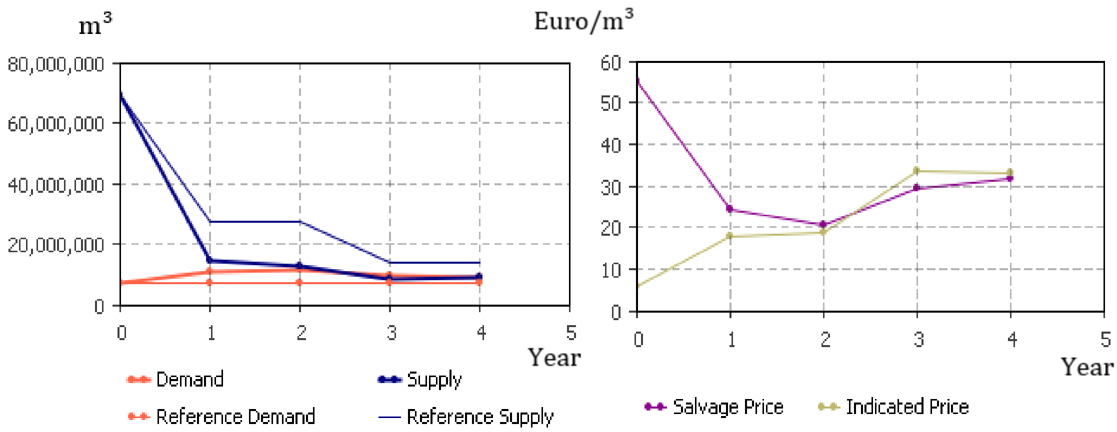

Figure 5.11: Determination of supply and demand of salvage (left), price setting process (right) of the salvage price submodel

The demand-supply balance illustrates whether demand exceeds supply. Figure 5.11 (left) shows that immediately after the third model year, the demand of salvage exceeds the supply, thereby increasing the indicated price. The indicated price which rises gradually during m odel runs, is calculated based on the initial salvage price and the demand supply balance on price (Figure 5.11, Right). The final salvage price is calculated based on the indicated price, initial salvage price and price adjustment time. During the first three years, the price declines from 55 to 21 Euro/m^3 but then the price grows again to 32 Euro/m^3 in the fifth year.

The influences of some of these parameters (e.g., PAT, demand elasticity and initial salvage price) on determining the final salvage price are discussed in the sensitivity analysis performed in Section 6.2.

5.3.4 Salvage value submodel

Salvage value is calculated for all of the 44 districts in Baden-Württemberg. For example, the district of Schwarzwald-Baar-Kreis (which is one of the most vulnerable districts in Baden-Württemberg), generates around 7.4 million m^3 of marketable salvage following the stochastic extreme storm. The simulation demonstrates that in the first three years, approximately 3.7, 1.5 and 1.5 million m^3 of salvage could be brought to the market having a value of 183, 29 and 24 million Euros, respectively. But the costs associated with salvage operation amount to roughly 30, 11 and 11 million Euros (Figure 5.12). The net value gained from selling salvage over the first five years is 153, 18, 13, 6 and 7 million Euros, which after considering a constant discount rate of 4.35% per annum, yields 147, 17, 13, 5 and 6 million Euros at present values.

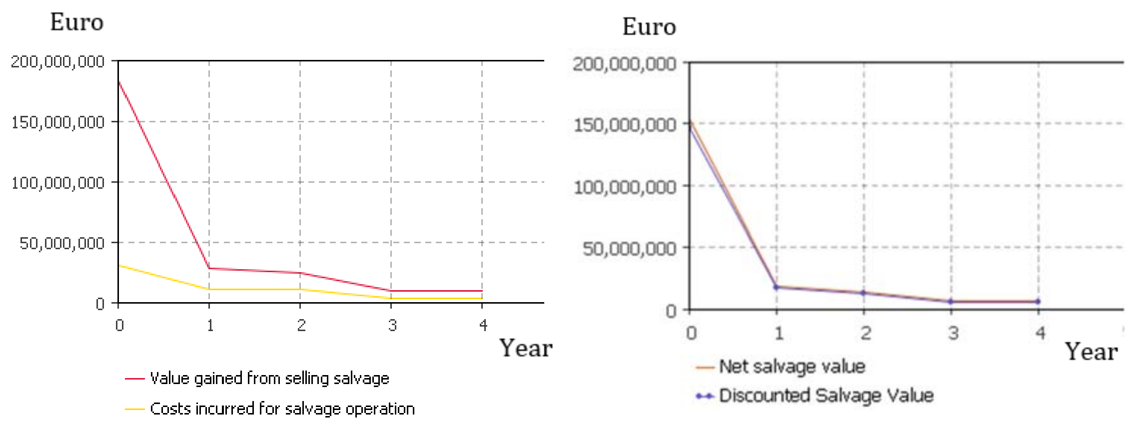

Figure 5.12: Salvage value gained and costs of salvage operation (left), net salvage value and discounted salvage value (right) in the district of Schwarzwald-Baar-Kreis

The discounted salvage value in all the districts in Baden-Württemberg is shown in Figure 5.13. Due to the degradation of salvage quality over time resulting in less marketable salvage, the net values reduce dramatically after the second year. The districts of Ortenaukreis, Freudenstadt and Schwarzwald-Baar-Kreis however, might experience maximum net monetary gains from the selling of salvage. The total net discounted salvage values in these districts is 206, 201 and 187 million Euros, respectively.

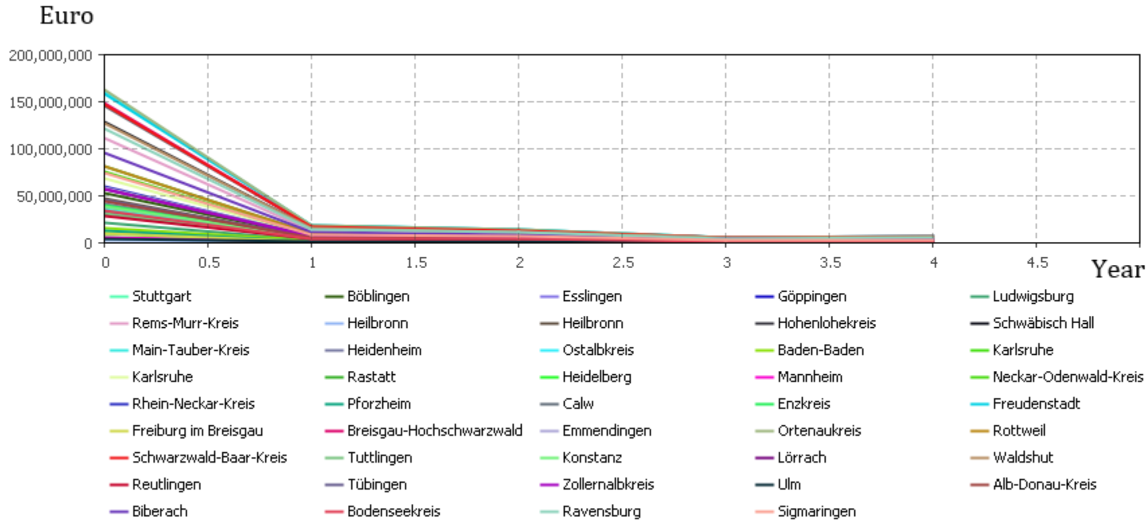

Figure 5.13: Discounted net salvage value in all the districts in Baden-Württemberg

5.3.5 Forest clearing area value submodel

The forest clearing area submodel is simulated for 20 years in all the districts. The costs associated with forest clearing areas originate from new tree plantation and the loss of potential timber value due to the storm. The total costs associated with tree plantation in the district of Schwarzwald-Baar-Kreis is approximately 500 million Euros, from which 400 million Euros is to be spent in the first year, the rest is equally spent in the following four years (Figure 5.14, left). The loss of potential timber value is low during the initial years but increases subsequently with the growth of timber, e.g., 0.9 million Euros in the first year but to around 26 million Euros after 20 years.

The total cost associated with forest clearing areas in this district is approximately 402 million Euros in the first year, then drops dramatically until the sixth year (6 million Euros) and then increases again to 26 million Euros in the twentieth year. The total sum of cost in 20 years would be 742 million Euros and after discounting the costs of each year for 20 years, the present value would be approximately 610 million Euros (Figure 5.14, right).

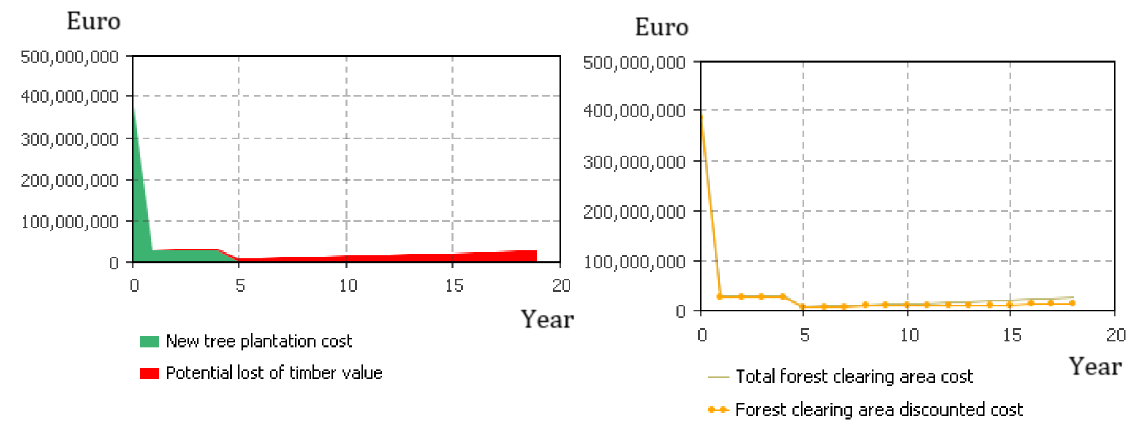

Figure 5.14: The cost of new tree plantation and potential loss of timber (left), total forest clearing cost and discounted cost (right) in the district of Schwarzwald-Baar-Kreis

Figure 5.15 shows the yearly discounted cost associated with the forest clearing areas in all the districts in Baden-Württemberg. The districts of Ortenaukreis (674 million Euros) and Freudenstadt (656 million Euros) experience - in terms of discounted present values - the maximum costs associated with the forest clearing areas in 20 years.

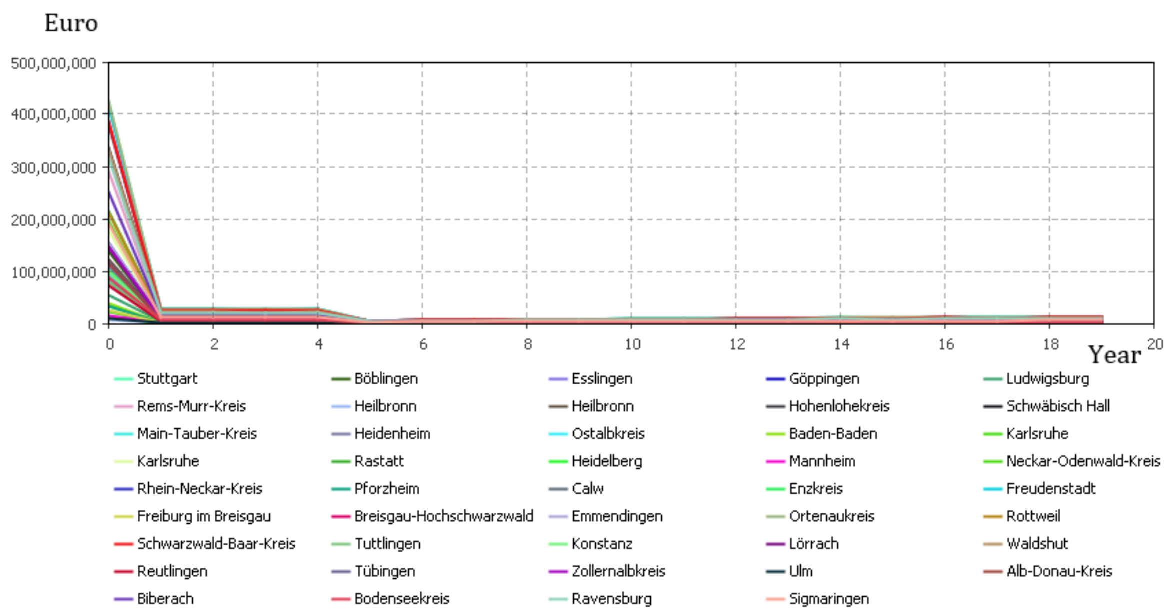

Figure 5.15: The discounted cost of forest clearing areas in the districts in Baden-Württemberg

5.3.6 Standing timber value submodel

The standing timber value within the areas unaffected by storm is also calculated for all the districts in Baden-Württemberg. The standing timber volume in the district of Schwarzwald-Baar-Kreis is approximately 8.73 million m^3, which in 20 years would grow to 9.02 million m^3, considering the reference growth and thinning rate of timber. The standing timber value and associated management costs are roughly 457 and 192 million Euros, respectively in the first year, but increase to 690 and 199 million Euros after 20 years (Figure 5.16, left). The growth of net standing timber value and associated discounted values for each year are shown in the Figure 5.16 (right).

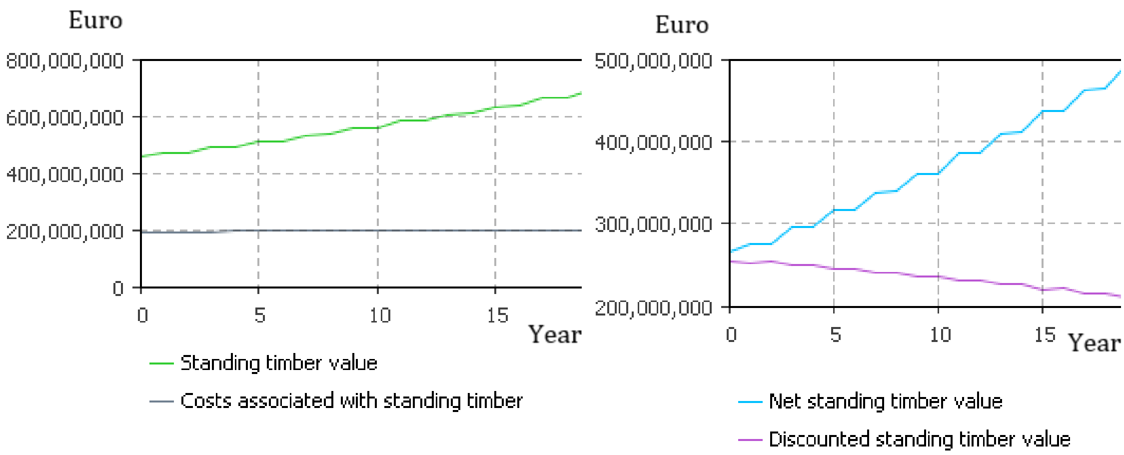

Figure 5.16: Standing timber value and associated cost (left), net standing timber value and its discounted value (right) in the district of Schwarzwald-Baar-Kreis

The discounted value of the standing timber in all the districts in Baden-Württemberg is illustrated in Figure 5.17. The districts of Ortenaukreis, Breisgau-Hochschwarzwald and Reutlingen enjoy a maximum net standing timber value with a value of 677 million Euros, 455 million Euros and 411 million Euros, respectively, in the first year.

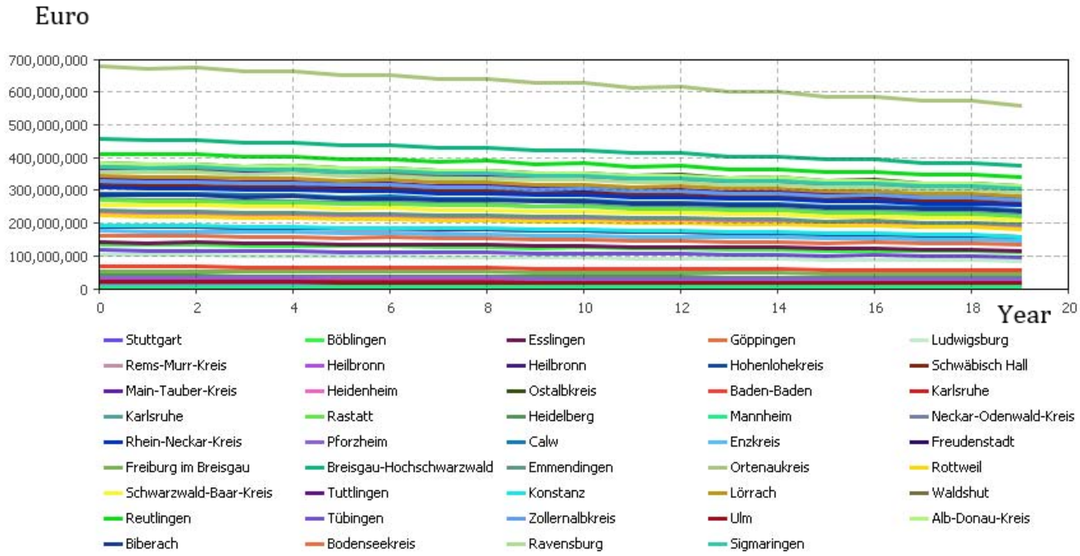

Figure 5.17: Discounted standing timber values in all the districts in Baden-Württemberg

5.3.7 Pre-storm timber value submodel

The pre-storm timber value submodel illustrates the pre-storm condition in all the districts of Baden-Württemberg. The total stock of timber volume in the district of Schwarzwald-Baar-Kreis is around 18 million m^3, and considering the current growth and thinning rate over 20 years, the volume would increase to roughly 18.8 million m^3.

The assumption regarding the development of timber price is shown in Figure 5.18 (left). The net timber value throughout the simulation years is calculated by considering the costs associated with timber harvesting and management, as well as the growth of timber price. The pre-storm timber value in this district increases from approximately 554 million Euros in the first year to 1,023 million Euros after 20 years (Figure 5.18, right).

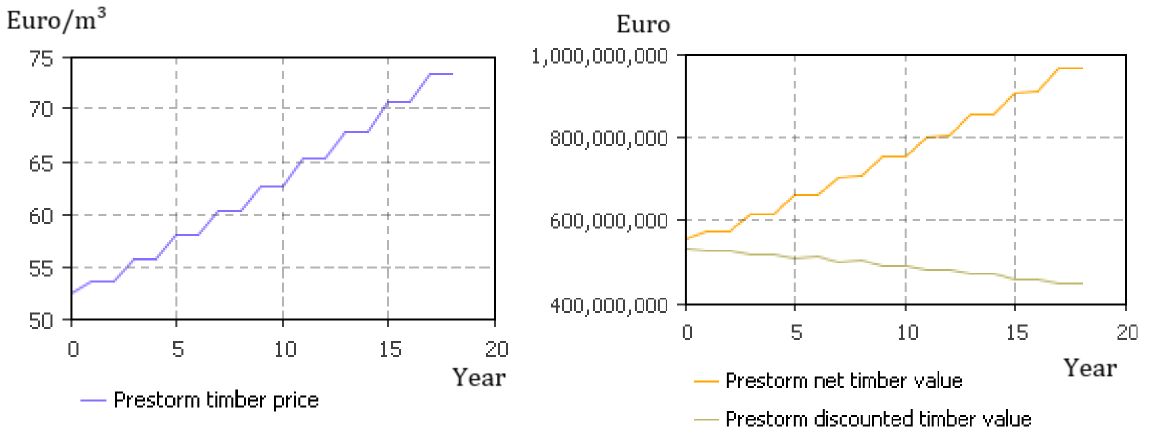

Figure 5.18: Pre-storm reference timber price (left), net timber value and discounted timber value (right) in the district of Schwarzwald-Baar-Kreis

Finally, Figure 5.19 illustrates the yearly discounted pre-storm timber values in all the districts in the state of Baden-Württemberg. The districts Ortenaukreis, Breisgau-Hochschwarzwald, and Ostalbkreis display maximum net present timber values throughout the simulation, e.g., 982, 732 and 683 million Euros, respectively, in the first year.

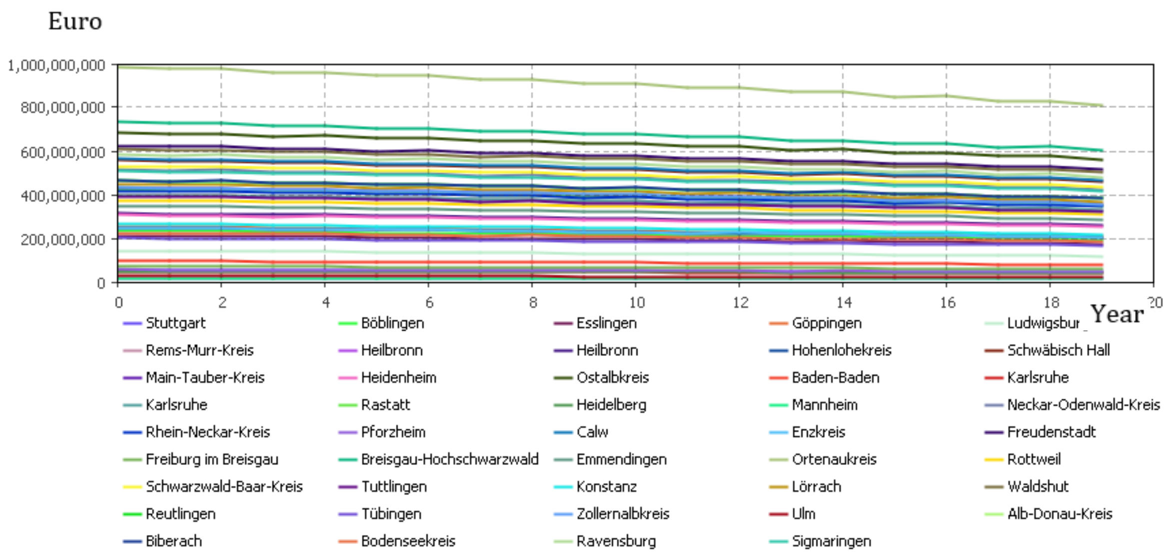

Figure 5.19: The discounted pre-storm timber value in the districts of Baden-Württemberg

5.3.8 Summary of results

The outcomes of reference simulation runs within the different submodels can be compared to identify the intensity of economic impact, and to understand how individual districts might become economically vulnerable or benefit from the storms. As explained in Section 5.3 and Section 5.4 so far, the pre-storm timber value submodel describes the reference scenario, without considering the occurrence of an extreme storm. The standing timber value submodel calculates the capital stocks or existing values (timber in areas unaffected by storms), whereas the salvage value submodel determines the possible positive cash flows (by selling salvage from storm affected areas), and the forest clearing area value submodel identifies the negative cash flows due to the cost incurred in storm affected areas. The net value gained or lost can thus be calculated and compared for each district at different simulation years. Considering the annual discount rate of 4.35%, the simulated values can also be calculated at present time values.

Figure 5.20 illustrates a comparative synopsis of the outcomes (discounted present values) of different submodels in the district of Schwarzwald-Baar-Kreis over the first, fifth and twentieth simulation year.

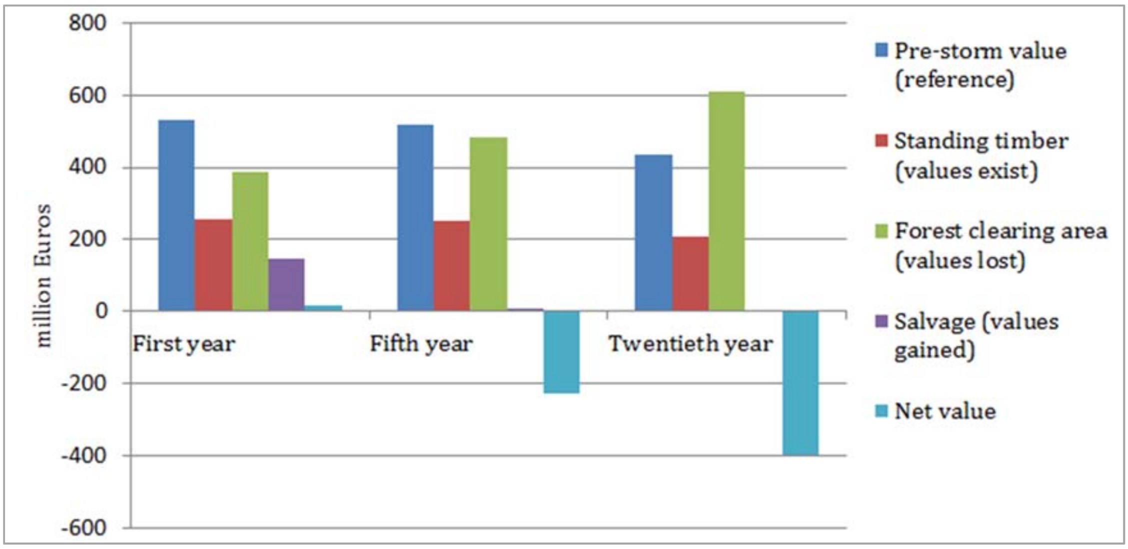

Figure 5.20: Comparison of discounted values of reference simulation runs of different submodels in the district Schwarzwald-Baar-Kreis

In the first year, against a total pre-storm timber value of around 531 million Euros, the stochastic storm would help to generate approximately 147 million Euros net positive cash flows when the salvage is sold, 385 million Euros negative cash flows due to the cost related to forest clearing areas. 255 million Euros worth of capital stock would be left as standing timber. The net value gained from such an event in the first year is roughly 17 million Euros. In the fifth year, no marketable salvage is available and the negative cash flows overpass the positive cash flows, leading to a total of around 229 million Euros net losses, considering the value in present time.

It is evident from the comparison that although the extreme storm initially offers positive cash flows, it has a long term negative impact. For instance, the present value of the discounted forest clearing area in the twentieth year is significantly higher than during the first years, which leads to a negative net value of 400 million Euros.

The net value gained or lost is significantly different within the districts. The regional differences are noticeable due to the varying amount of forest resources, differences in vulnerabilities due to winter storms, etc. All the districts except Mannheim experience net gain from selling of salvage over the first year. The district Ortenaukreis, Reutlingen, Alb-Donau-Kreis and Main-Tauber Kreis would gain a net value of over 300 million Euros each by selling salvage (Figure 5.21).

Over the fifth and twentieth simulation year, the net value gained reduces significantly among the districts. The districts of Schwarzwald-Baar-Kreis, Freudenstadt, Rems-Murr-Kreis, etc. continue to experience significant losses due to the extreme winter storm. Figure 5.21, Figure 5.22 and Figure 5.23 illustrate the spatial distribution of the discounted net value over the first, fifth and twentieth simulation year, respectively, in all the districts in Baden-Württemberg.

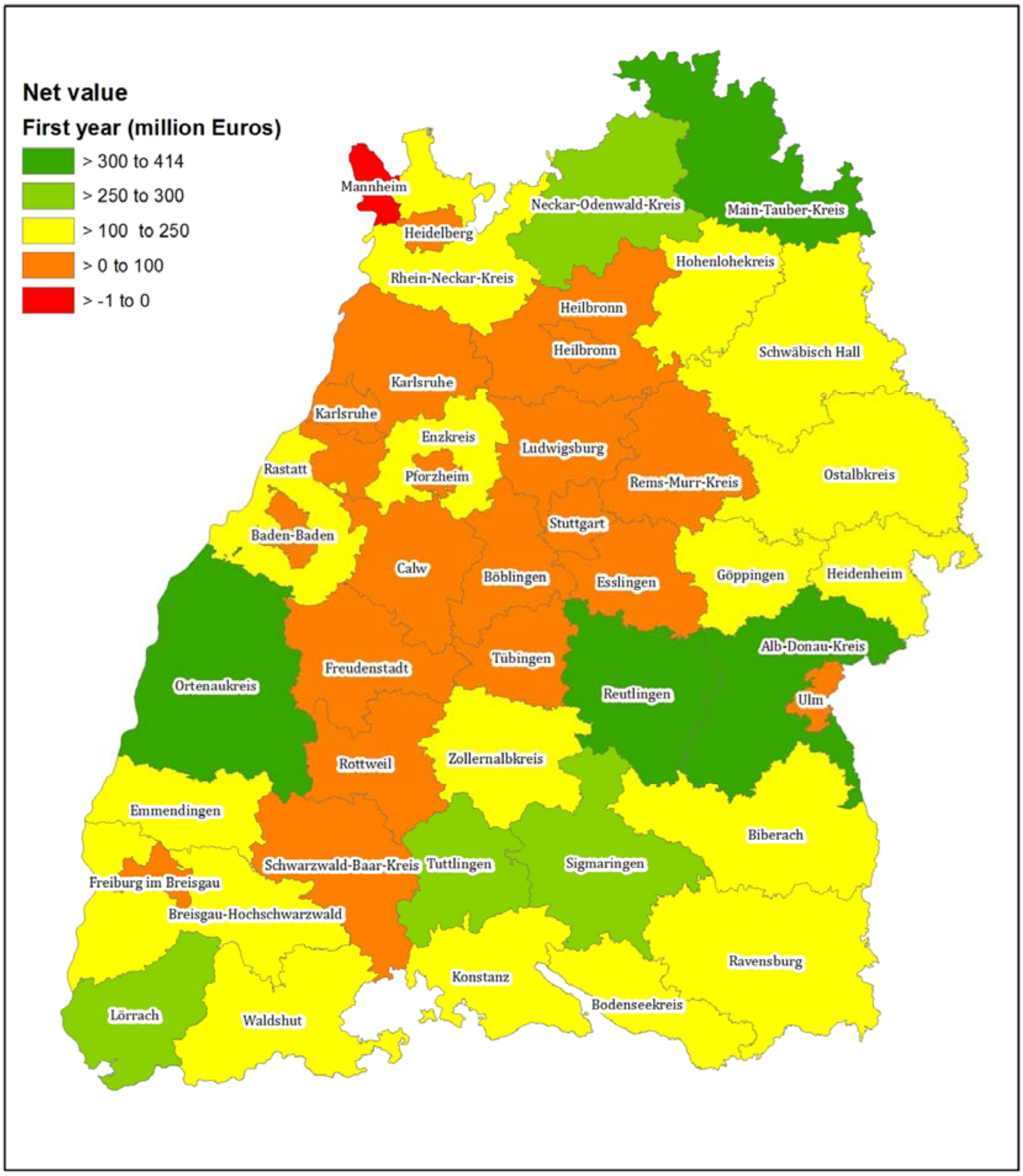

Figure 5.21: Spatial distribution of net value gained or lost in the first year

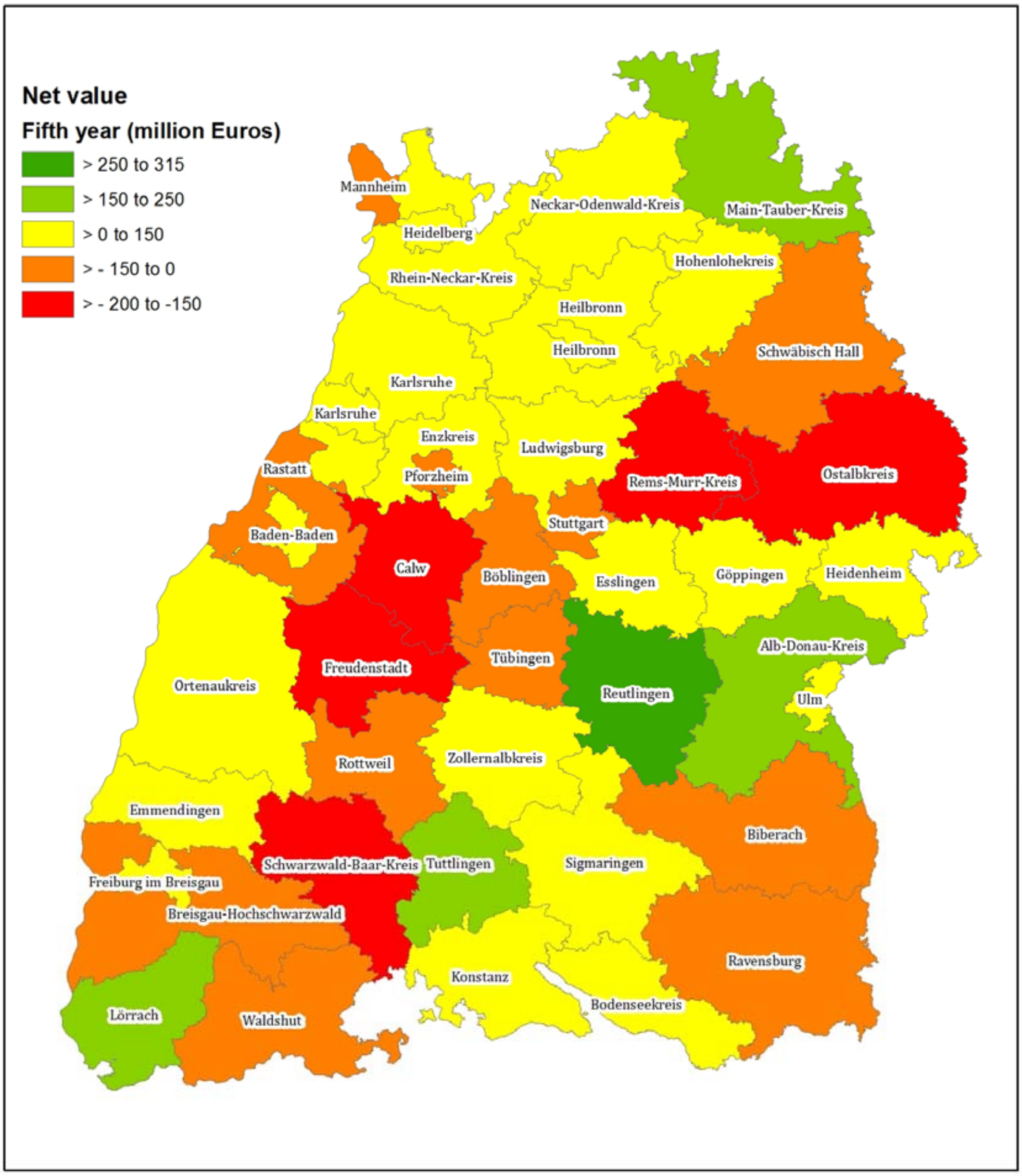

Figure 5.22: Spatial distribution of net value gained or lost in the fifth year

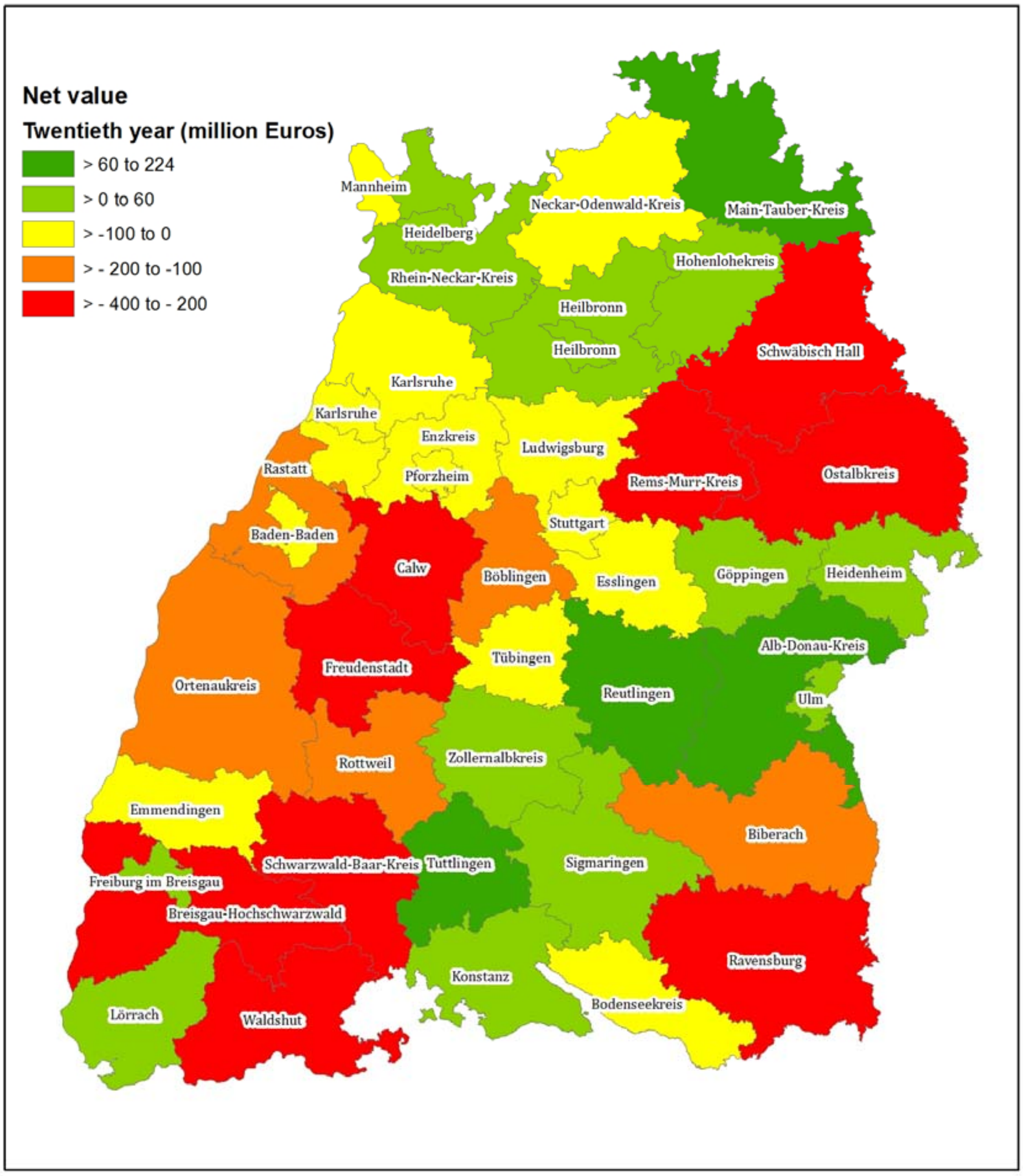

Figure 5.23: Spatial distribution of net value gained or lost in the twentieth year

Such analysis will help the forest managers to understand the impacts of an extreme winter storm and thus assist in the planning of alternative risk management strategies for specific districts or regions. In this regard, local adaptation and mitigation strategies can be incorporated into the silviculture management policies of each district.

Moreover, by simulating these types of possible future impacts, forest managers and owners would be able to organize marketing strategies in order to control the sale of salvage timber and to prevent the depreciation of its value, after an extreme winter storm. The net value gained or lost is very important since the total costs incurring in forest clearing areas, during salvage operation can be important, and the value of the wood as standing timber is tied up for a prolonged period of time. To overcome potential losses and to reduce the economic impact of extreme storms, alternative marketing strategies can be prepared. Two such alternative policy based scenarios are discussed in Section 6.1.

5.4 Validation and model testing

5.4.1 Validation in system dynamics literature

Validation refers to the testing of the model output in order to reject or to confirm the results in comparison to the reality (Fishman & Kiviat, 1968). Model validation or testing helps to discover flaws in a model and helps to improve the understanding of the model. A model should be built for a specific purpose (or application) and validity determined with respect to that purpose (Sargent, 2013). (Rykiel, 1996) provided an overview of how validation has been employed in modelling and distinguishes (i) operation or whole-model validation (correspondence of model output with real world observations) (ii) conceptual validation (evaluation of underlying theories and assumptions) and (iii) data validation (evaluation of the data used to test the model). At least 13 different categories of validation procedures are commonly discussed, explicitly or implicitly in literature (Wainwright & Mulligan, 2013).

Regarding the exigencies of operation and conceptual validations, the validation of system dynamics models should be a comprehensive process of 'building confidence' in the underlying assumptions of a model (J. W. Forrester & Senge, 1980). System dynamics models are built to fulfil a purpose and the structure of the model drives its behaviour (J. W. Forrester, 1961). Its validity is determined by the extent to which it satisfies that purpose (J. W. Forrester & Senge, 1980). (Qudrat-Ullah, 2005) explained that for policy models, the key issues in validation are to decide (i) if the model is acceptable for its intended use, i.e., does the model mimic the real world well enough for its stated purpose (J. W. Forrester, 1972; J. W. Forrester & Senge, 1980) and (ii) how much confidence can be placed in model-based interfaces of the real system (Barlas, 1989). Therefore, the process of building confidence in a system dynamics model can be explained by a set of structural and behavioural tests. (Sterman, 2000) proposed a total of 6 structural validity tests and 10 behavioural validity tests. A comprehensive discussion of these tests and some case studies are given in (J. W. Forrester & Senge, 1980), (Qudrat-Ullah & Seong, 2010), (Barlas, 1996).

The review of various system dynamics models and related literature reveal a rather limited implementation of system dynamics validation tests. Out of about 20 system dynamics related case studies, only five studies performed validation and testing of their models. However, in this research, some of the most important structural and behavioural tests are performed which might help to enhance the overall acceptance of this type of simulation model results and of policy and scenario analysis explained in Chapter 6.

The identification of an appropriate structure is the first step to establish validity of a system dynamics model. Accordingly, the behavioural validity is then assessed to evaluate the overall validity of the model and to build confidence in the model (Sterman, 2000).

5.4.2 System dynamics validation applied in this study

5.4.2.1 Structural validity

Structural validity ensures the 'right behaviour for the right reasons' and becomes the core of the system dynamics modelling validation process (Barlas, 1989). Since the search for structural validity needs to involve stakeholders of the model, modellers, clients and policy researchers, it is argued that structural validity is a stringent measure to build confidence in a system dynamics model regardless of how well the model passes a behavioural validity test. (Qudrat-Ullah & Seong, 2010), (J. W. Forrester & Senge, 1980) discussed several tests for structural validation. Some of the most important tests are structure verification, parameter verification, extreme condition and boundary adequacy, each of which critically inspects different aspects of the model. Table 10 describes the structural validation tests, their purposes and approaches as undertaken in this research.

Table 10: Selected structural validation tests and corresponding approaches[9]

Structural validation type	**Purpose**	**Approaches**
Structure verification	Whether the model structure is consistent with relevant descriptive knowledge of the system being studied?	a. Reviewed system dynamics literature and followed system dynamics modelling paradigm.

[9] Modified after (Qudrat-Ullah & Seong, 2010), (Sterman, 2000), (Barlas, 1996).

		b. Adaptation and integration of existing system dynamics model structures, e.g., price discovery model (Sterman, 2000). c. Consultation with the forester to understand the forest management practices. d. Reviewed relevant literature and associated data in the context of Baden-Württemberg and Germany to understand the forestry resources and management. e. The causal relationship developed in the study, provides empirical structural validation (Zebda, 2002).
Parameter verification	Whether the parameters in the model are consistent with relevant descriptive and numerical knowledge of the system?	a. The parameterization is based on relevant literature, current forest practices, statistical data and expert knowledge. All sources are properly referenced in Table 9. b. Moreover, the definition and assumption of model parameters and variables are also described in Section 2.3.4 and Section 5.3.
Extreme conditions	Whether the model exhibits a logical behaviour when some selected parameters are assigned extreme values?	Four parameters are tested with extreme values, e.g., significantly low price elasticity of demand (e.g., -10), etc. and checked whether the models perform according to anticipated behaviour. Explained in Figure 5.24 and Figure 5.25.
Boundary adequacy	Whether the important concepts and structures for addressing the policy issues are endogenous to the model?	a. Most of the important concepts addressing policy issues and major aggregates are derived endogenously. For example, final salvage price is defined endogenously. b. The boundary conditions, i.e., all endogenous, exogenous and excluded variables are described in Figure 5.2.
Dimensional consistency	Whether each equation in the model dimensionally corresponds to the real system?	a. The dimensional consistency of each of the mathematical equations of the system dynamics model is critically checked and evaluated during each submodel run. b. Moreover, the dimensions are illustrated in Section 5.4.1 and Appendix 5.

The extreme condition test is performed by varying some of the critical parameters, e.g., sale percentage, salvage degradation factor, discount rate, annual percentage of salvage sale, etc. With a significantly low price elasticity of demand (e.g., -10), the final salvage price remains mostly stable and the model does not show erratic behaviour (Figure 5.24, left). Changing of salvage price adjustment time from 1 year to 1 week, reduces the salvage price dramatically to 10 Euro/m^3 in the second year, and then adjusts slowly in later years (Figure 5.24, right). The degradation factor and discount rate are tested with zero values and the submodels show expected behaviour (Figure 5.25).

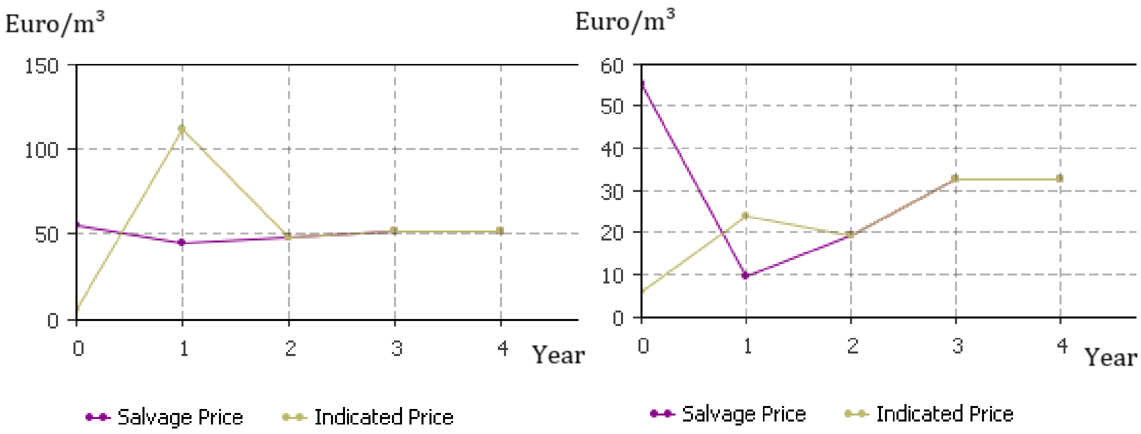

Figure 5.24: Extreme conditions test with price elasticity of demand -10 (left) and price adjustment time 1 week (right) in salvage price submodel

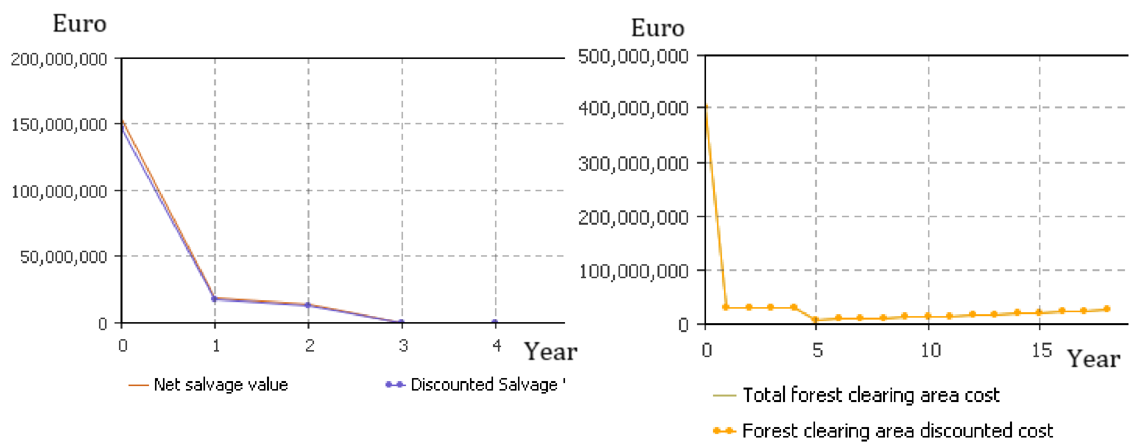

Figure 5.25: Extreme conditions test with degradation factor zero in the fourth and fifth simulation year of salvage value submodel (left), and discount rate zero throughout the simulation run in forest clearing area value submodel (right)

5.4.2.2 Behavioural validity

The main purpose of testing behavioural validity is to compare the model-generated behaviour to the observed behaviour of the real system (Qudrat-Ullah & Seong, 2010). (Sterman, 1984) proposes statistical techniques for assessing the quality of fit between a system dynamics model and historical data. (Wolstenholme, 1990) and (Mohapatra, Mandal, & Bora, 1994) applied such methods proposed by (J. W.

Forrester & Senge, 1980). However, (Kiani & Pourfakhraei, 2010) conducted a validation with historical trends and concluded that the future trends cannot be justified by historical behaviour. However, since the simulated behaviour follows the model's structure and behaviour, it is expected that the prediction of the model's future behaviour will be logical. Moreover, a success in matching historical data with the model outcome does not ensure the reliability of forecasts. (Sterman, 2000, p. 331) notes that 'the ability of the model to replicate historical data does not, by itself, indicate that the model is useful'.

In this research two important behavioural validation tests - behaviour reproduction and behaviour sensitivity - are undertaken (Table 11).

Table 11: System dynamics behavioural validation tests

Behavioural validation type	Purpose	Approach
Behaviour reproduction	Whether the model reproduces the behaviour of a real event (qualitatively and quantitatively)?	Due to unavailable historical data comparable to the model output, statistical analysis is not possible to perform.
Behaviour sensitivity	Whether sensitivity of values, behaviour and policy implications to variation of uncertain parameters do exist?	Software based sensitivity analysis of some uncertain parameters (e.g., demand elasticity, price adjustment time, discount rate, etc.) are performed and discussed in Section 6.2.

The purpose of a behaviour reproduction test is to check whether the model reproduces the behaviour of interest. It is generally done by comparing the model outcomes with historical data. Unfortunately, the outcome of each of the submodels cannot be directly compared and tested with similar historical data for many reasons, for instance:

- Data on such comparable extreme winter storms is not available.
- The WofE model applied in Chapter 3 does not imitate or refer to a specific historical storm; rather it identifies the posterior probability map of vulnerable forest areas of different magnitudes, based on different weather and site related factors.
- The WofE model predicts vulnerability based on the conditions present in the whole state of Baden-Württemberg, thereby identifies vulnerable areas

at a larger extent, compared to any historic real storm. For example, Storm Lothar damaged only a part of the forests in the Black Forest.

- This study aims to address the problems associated with forests after extreme winter storms. The simulated system dynamics model behaviours and corresponding outcomes are completely dependent on the model boundary conditions defined for this study. However, the real forest system is highly complex and might show different characteristics after a storm. For example, internal dynamics of trees, uncertainties on timing and conditions during the storms, local adaptation and resilience capabilities, forest owners' decisions, price developments of salvage and timber, etc. are difficult to anticipate beforehand.
- Nevertheless, the development of the salvage price within the model follows a trend similar to previous storms (see Section 2.3.4.6) and reveals a price reduction of 56%, 63%, 46% and 42% in the second, third, fourth and fifth year, compared to the reference salvage price in the first year (Figure 5.11).

5.4.2.3 Data validity

The validation of the data is performed to determine whether the data required for model building, validation and experimentation are sufficiently accurate (Robinson, 1997). In this research, an extensive amount of data is collected to build the conceptual model and the system dynamics simulation model. The reliability and suitability of the data is explored and verified by mentioning the appropriate sources (see Section 2.3.4 and Section 5.4.2). In some cases, reasonable assumptions with respect to the real world have been made through consultation with the forest managers.

Moreover, the input data is stored separately (e.g., in spreadsheets) from the simulation code to facilitate easy identification of errors and updates or further improvement of model, as more accurate or detailed data becomes available in future.

5.5 Summary and further research steps

In this chapter, the impact of extreme winter storms on the forest resources is analysed with a system dynamics modelling framework. Such approach offers a comprehensive understanding of the problems forestry faces after winter storms. The use of dynamic feedbacks in simulating the behaviour of different sub-sectors in forestry – e.g., the positive and negative cash flows incurred in salvage operation or in forest clearing areas across all the districts in the state of Baden-Württemberg

– could help forest managers and owners to operate the forest in a more sustainable way.

One of the initial objectives of this system dynamics model is to examine various policies relevant to the management of forest resources after an extreme winter storm. Grounded on such policies, alternative scenarios could be developed and tested using the proposed modelling framework. Scenarios would enable forest managers and owners to more accurately evaluate the outcome of different strategies which can be compared with the reference scenarios. In this way, the forest management plan for 10 years and onwards could be optimised. Therefore, some policy based alternative scenarios are designed and corresponding submodel outcomes are evaluated in **Chapter 6**.

Moreover, sensitivity analyses can identify the influence of uncertain model parameters to the endogenous parameters, as well as to overall model results. They are tested by increasing and decreasing certain parameters which are crucial, considering the uncertainties and importance associated with assumptions and selection of reference values. Therefore, the sensitivity analyses of some of the most important and uncertain input parameters are performed in Chapter 6.

6 Policy Based Scenario and Sensitivity Analysis

6.1 Selection of Policy and scenario building

A scenario is an analysis tool that describes a possible set of future conditions. The most useful scenarios for policy planning are those that display the conditions of important variables over time (Moniz, 2005).

The system dynamics framework is used to model and generate scenarios since it has the capability of representing physical and information flows - that will enable us to understand the non-linear dynamic behaviour in uncertain conditions (Suryani, Chou, Hartono, & Chen, 2010). The main focus of the system dynamics model lies on forecasting the mutual behaviour of key variables of different sub-models. Therefore, compared to other methods, system dynamics enables a consideration of interdisciplinary issues.

Two types of scenario analysis - structure scenario and parameter scenario - can be performed in system dynamics (Suryani et al., 2010). Structure scenarios are generated by adding feedback loops, changing the structure of the feedback loop or adding new parameters. Parameter scenarios are generated by changing the value of exogenous parameters. By varying them, different scenarios can be built to evaluate the impact of salvage operation decision options in the future. In this regard, evaluations related to economic variables, e.g., price, elasticity, etc. are given main importance.

Based on a thorough literature review, different alternatives of policy design and scenario analysis have been developed for this research, after several reiterative consultations with the forest administrators and researchers. The scenarios do not represent any particular government policy currently in place, in the past or in the future. Rather they answer 'what if' questions and represent a range of possible management policies in storm affected forest regions. Workshops were organized to identify these policies and possible responses that might be needed after an extreme storm.

- The first workshop was held at the Karlsruhe Forest Department with forest managers and operators on 25th November 2014. It was complemented by a field visit to the storm affected forest areas in the North Black Forest region.
- The second workshop was organized at the Chair of Financial Economics and Risk Management in KIT on 6th February 2015, with the participation of a forest manager and faculty.
- Earlier in 2012 and 2013, several individual meetings with a treasury of the Freudenstadt Municipality Forest Department[1], a manager and a owner of a sawmill industry[2], as well as the system dynamics experts in EIFER were organized.

Based on these workshops and meetings, two alternative policies - along with the reference simulation scenario - were identified:

- Immediate salvage operation,
- Delayed salvage operation.

The immediate salvage operation policy portrays scenarios where most of the salvage would be sold out within the first year, in order to achieve maximum profit, as the quality of the salvage is still good. At the same time, during this short period, a comparatively small amount of salvage would be stolen. But, due to an excess supply of timber in the market, the salvage price might be lower than in future years. Therefore, the price elasticity of demand would be lower than the reference elasticity. Moreover, due to shortage of manpower, the salvage operation cost could also increase, compared to the reference scenario.

The delayed salvage operation policy resembles a sustainable and ecological scenario, where only little salvage is sold out during the first few years. Here, most of the salvage is assumed to be left out in the forest for longer time, which would lead to a deterioration of salvage quality in later years. The risk of theft of salvage will also be increased. In this policy, the market does not experience excess supply of timber and thus the salvage and timber price do not fall dramatically. Therefore, the price elasticity of demand would be higher than that of the reference simulation. Table 12 explains these two policies, along with the assumptions on relevant parameters[3] and input values.

[1] Mrs. Birthe Hagen is the treasury (*Kämmerei)* of the Freudenstadt Municipality.
[2] Mr. Hannes Marx is the manager and Mr. Karl Geiser is the owner of the sawmill industry "Gaiser Karl & Sohn GmbH" in Baiersbronn.
[3] The other parameters within the different submodels remain the same as in the reference simulation run.

Table 12: Two policy based scenarios, parameters and their input values[4]

Policy name	Demand elasticity	Stolen salvage (%) [5 years]	Sale (%) [5 years]	Logging cost (Euro/m^3) [5 years]
Immediate Salvage Operation	- 1	[1, 2, 2, 2, 2]	[70, 10, 10, 5, 5]	[10, 7, 7, 7, 7]
Delayed Salvage Operation	- 0.1	[4, 4, 2, 2, 2]	[10, 20, 50, 10, 10]	[7, 7, 10, 7, 7]
Reference Run	- 0.5	2	[50, 20, 10, 10, 10]	7

6.2 Effects of different policies

6.2.1 Policy of immediate salvage operation

Immediate salvage operation policy would bring approximately 98 and 14 million m^3 of salvage to the market in the first two years, against a reference demand of 7 million m^3 (Figure 6.1, left). With the influence of lower price elasticities of demand and higher supply, the supply rises more than the demand (i.e., demand supply balance is less than 1) in the second year, which leads to a drop of salvage price to 24 Euro/m^3. But later, due to decreasing supply, the price steadily rises up to 53 Euro/m^3 in the fifth year (Figure 6.1, right).

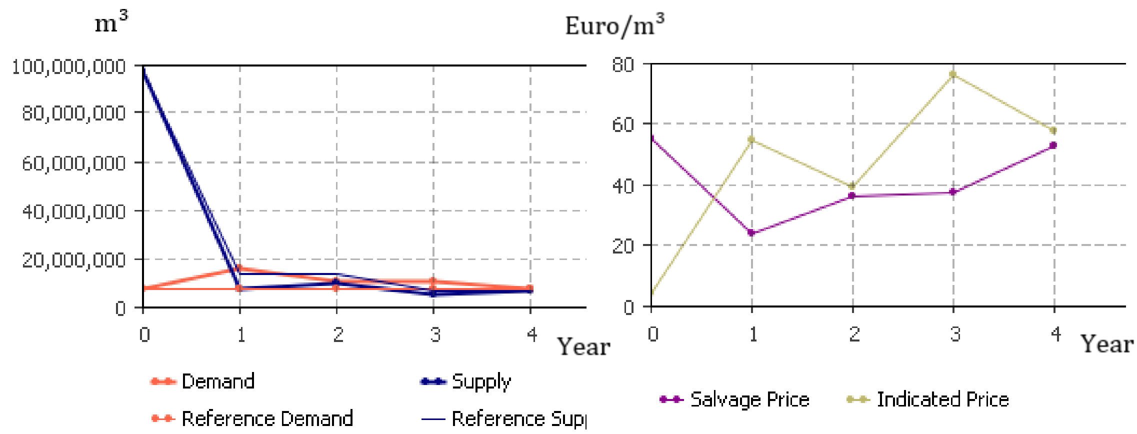

Figure 6.1: Effect of immediate salvage operation policy on the development of salvage price

[4] The five numbers in square bracket represent the input values for each simulation time step (i.e., first, second, third, fourth and fifth year).

In the district of Schwarzwald-Baar-Kreis, approximately 7.4 million m^3 of marketable salvage are available. During five years, against a total salvage value worth of 308 million Euros, the cost incurred in salvage operation is roughly 70 million Euros (Figure 6.2, left). The total net salvage value is about 283 million Euros (in the first three years around 202, 9 and 15 million Euros, respectively) and the net present value of total salvage is around 226 million Euros (Figure 6.2, right).

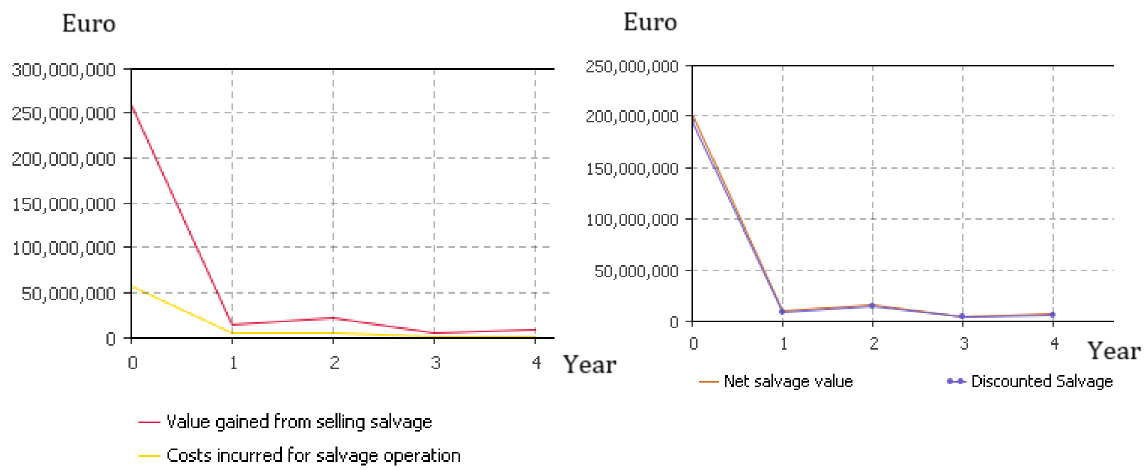

Figure 6.2: Development of salvage value and associated cost in the scenario of immediate salvage operation policy in the district of Schwarzwald-Baar-Kreis

Figure 6.3 shows the variations of discounted salvage values in all districts in Baden-Württemberg.

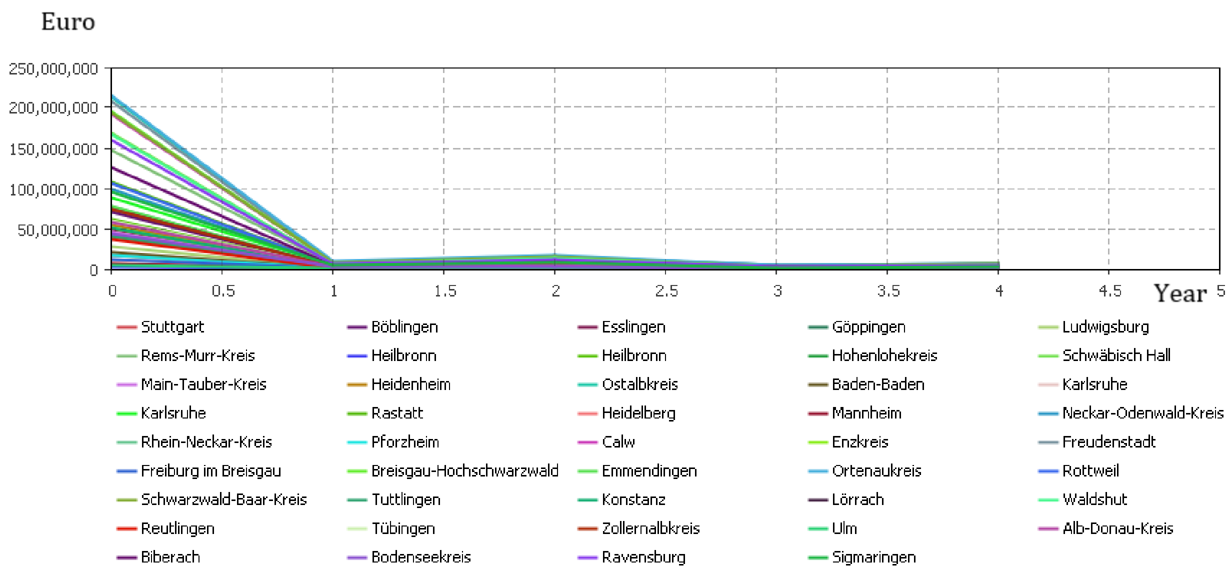

Figure 6.3: Discounted net salvage value in immediate salvage operation policy in all districts in Baden-Württemberg

6.2.2 Policy of delayed salvage operation

Delayed salvage operation policy would bring around 14, 27 and 27 million m^3 of salvage to the market over the first three years, against a reference demand of 7 million m^3 (Figure 6.4, left). The supply remains higher than the demand until the third year. But with the influence of price elasticity of demand and other factors, the salvage price drops steadily until the fourth year, to 11 Euro/m^3, but then rises again in the fifth year (Figure 6.4, right).

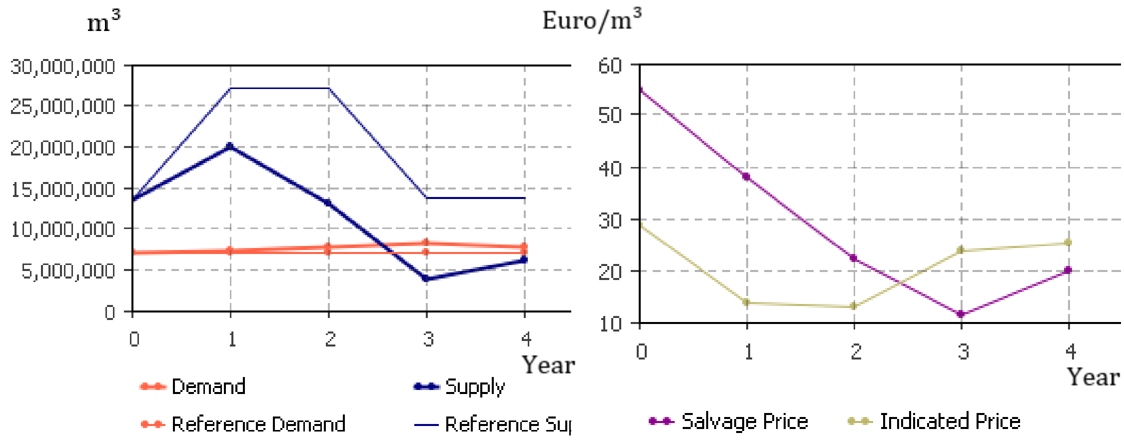

Figure 6.4: Effect of delayed salvage operation policy on the development of salvage price

In the district of Schwarzwald-Baar-Kreis, the delayed salvage operation policy brings approximately 5.1 million m^3 of salvage into the market, with a quantity of roughly 0.72, 1.5, 1.5 million m^3 over the first three years. The aggregated value of the salvage after 5 years is approximately 115 million Euros, whereas the operation cost amounts to around 32 million Euros. The net salvage value of 83 million Euros is originated mainly over the first two years (30 and 33 million Euros, Figure 6.5, left). In the third and fourth years, the salvage quality and price reduce sharply which leads to a reduction of salvage value (Figure 6.5, right). After discounting, the net present value of the total salvage is approximately 77 million Euros. Figure 6.6 shows the trend of discounted salvage values in all districts in Baden-Württemberg.

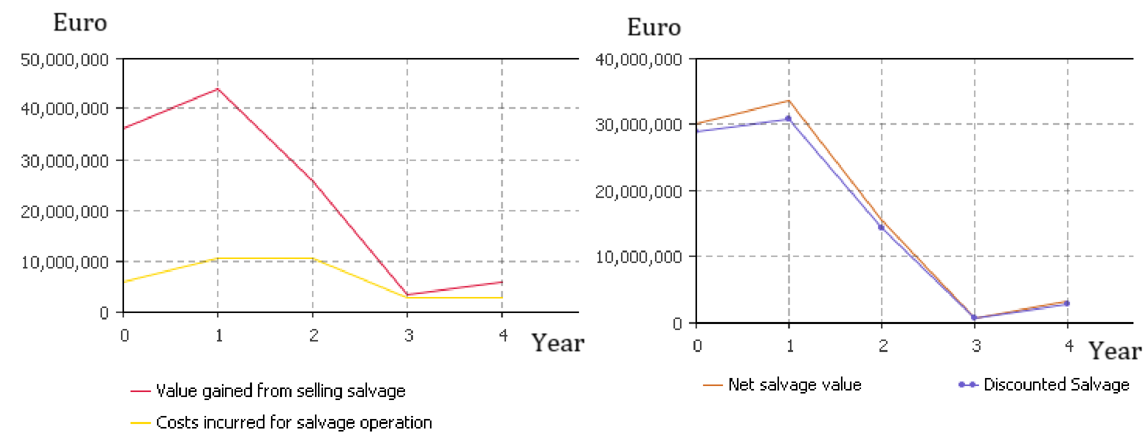

Figure 6.5: Development of salvage value and associated cost in delayed salvage operation policy in the district of Schwarzwald-Baar-Kreis

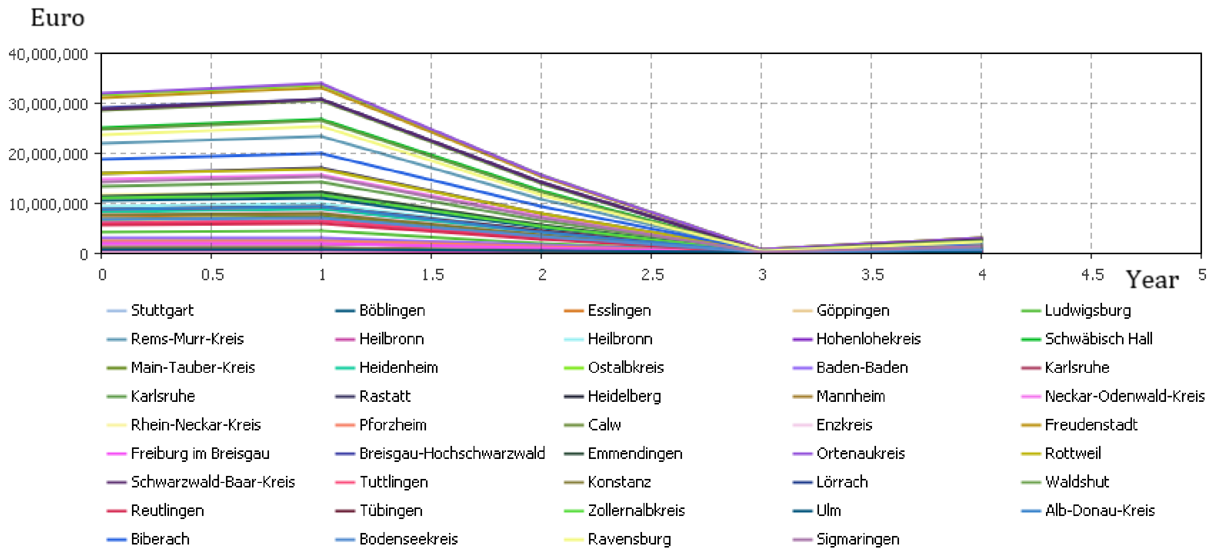

Figure 6.6: Discounted net salvage value in the delayed salvage operation policy

6.3 Sensitivity analysis

6.3.1 Assessing the effect of selected parameters

In modelling, as a general rule of thumb, one should invest in parameter measurement according to how big an effect the parameter has on the model output of interest. The magnitude of the effect of parameters on model output is known as the sensitivity of a model to its parameter (Wainwright & Mulligan, 2013). Sensitivity analysis is the process of defining how changes in model input parameters affect the changes in model output. Along with validation, sensitivity analysis can also be used as a method to experiment with the model. It is primarily used to better understand the behaviour of parts, or the whole system being modelled.

(Saltelli, Chan, & Scott, 2000) and (Hamby, 1994) analysed different methods of sensitivity analysis. In most cases, a single parameter is varied incrementally around its standard value, keeping all other parameters unaltered (Wainwright & Mulligan, 2013). The model outputs of interest are monitored in response to these changes and the model sensitivity is usually expressed as the proportional change in the model output per unit change in the model input. Different input parameters can be tested and the most sensitive or insensitive parameters can be defined.

In system dynamics, generally, sensitivity analysis can be conducted to evaluate the effect of changes in model parameters on economic welfare estimates. Unfortunately, compared to scenario analysis, very few system dynamic based studies[5] have performed sensitivity analysis.

The sensitivity analysis in this research is performed considering the 'one-at-a-time' method by varying the value of one parameter at a time, while keeping the values of other parameters constant (Wei, Yang, Song, Abbaspour, & Xu, 2012). For example, elasticities of supply and demand, with respect to price can be halved and doubled. Discount rate can also be increased and decreased to a certain percentage to observe the effect.

Therefore, in this research, four parameters are identified as crucial and therefore, are tested to ascertain the level of uncertainty in model outcomes. The minimum and maximum values of those four parameters are derived based on the expert judgement during the modelling workshops as well as based on the insights from the literature review. The parameters selected are:

- Elasticity of demand with respect to salvage price, which is decreased to -1 and increased to 0.5,
- Price adjustment time, which is decreased to 3 months (0.25 years) and increased to 1.5 years,
- Salvage reference price, which is decreased to 30 Euro/m^3 and increased to 70 Euro/m^3,
- Discount rate, which is decreased to 2% and increased to 8%.

[5] E.g., (Rooney et al., 2013), (Jones, 2009), (Vogstad, 2004), etc.

An overview of the parameter selection and their minimum and maximum values is represented in Table 13. For each parameter, discrete steps between the minimum and maximum values are chosen to perform the sensitivity analysis.

Table 13: Selection of parameter and their variation in sensitivity analysis

Selected parameter	**Reference value**	**Min**	**Max**	**Number of simulation run**
Demand elasticity	-0.5	-1	0.5	4
Price adjustment time of salvage (year)	1	0.25	1.5	6
Salvage reference price (Euro/m^3)	55	30	70	5
Discount rate (%/year)	4.35	2	8	4

6.3.2 Range of sensitivities

6.3.2.1 Sensitivity of demand elasticity

The price elasticity of demand is tested considering a minimal value of -1 up to the maximum value of 0.5, with a step of 0.5, resulting in 4 model runs that show the impact of the price elasticity of demand on salvage price.

With an initial salvage price of 55 Euro/m^3, the salvage price in the second year remains between 23 and 25 Euro/m^3, but in later years the difference increases (Figure 6.7). For example, an increase of demand elasticity from -0.5 to 0.5, reduces the salvage price from 30 to 10 Euro/m^3 in the fourth year, and a decrease of elasticity to -1 increases the price to 36 Euro/m^3. The same behaviour is observed in other simulation runs, which confirms that the price elasticity of demand is sensitive to the final salvage price.

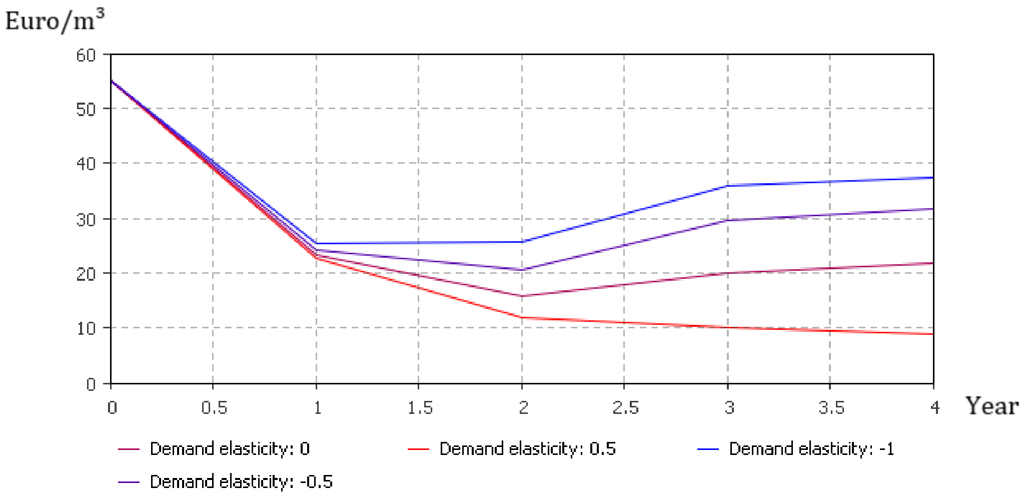

Figure 6.7: Sensitivity of price elasticity of demand on salvage price

6.3.2.2 Sensitivity of price adjustment time

The impact of price adjustment time (PAT) on salvage price is tested considering a minimum time of 0.25 years (3 months) to the maximum of 1.5 years with a step of 3 months, which leads to 6 model runs in total. The impact of varying PAT inflicts a maximum variation of the final salvage price mostly in the second year (Figure 6.8).

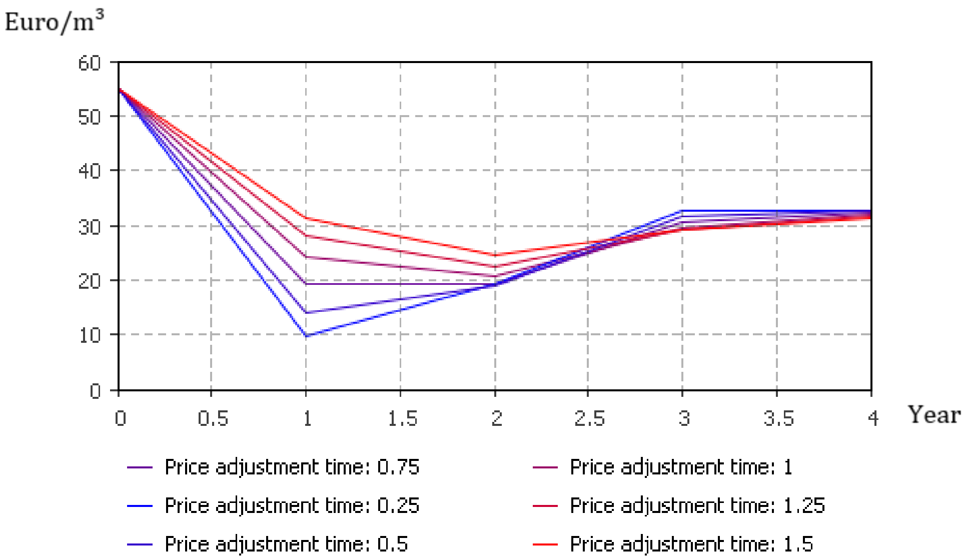

Figure 6.8: The sensitivity of price adjustment time to the final salvage price

In later years, the variations of price reduce considerably. It is also evident that a consideration of lowest PAT, reduces the final salvage price in the second year, and increases the prices in the fourth and fifth year. For example, assuming that the market reacts very quickly (with 3 months PAT), the salvage price reduces by about

82% (10 Euro/m^3) in the first year, which is 56% (24 Euro/m^3) reduction, compared to that of the reference simulation (with 1 year PAT). However, in the fourth year, both prices adjust to 33 and 30 Euro/m^3, respectively.

The PAT is found elastic over the initial year. So the selection of an appropriate price adjustment time is crucial as it has significant impact on the final salvage price, especially during the first two years.

6.3.2.3 Sensitivity of salvage reference price

The impact of the initial salvage reference price on the final salvage price is tested by varying the initial price between 30 Euro/m^3 and 70 Euro/m^3, with a discrete step of 10, which leads to a total of 4 simulation runs. In all runs, the final salvage price development follows a similar trend from the first year to the fifth year. For example, prices tend to fall until the third year, then increase in the fourth and fifth year (Figure 6.9). Nevertheless, the final values of different model years are dependent on the initial salvage prices, and follow a similar degree of change. For example, with an initial salvage price of 70 Euro/m^3, the final salvage price in the second and third year reduces by 56% and 63%, respectively. Similar patterns of percentage change are also observed in all other simulation runs.

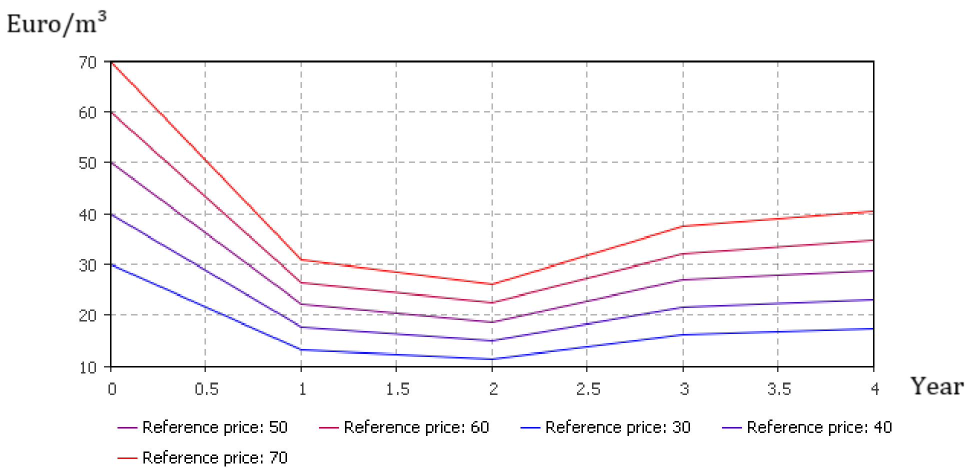

Figure 6.9: The sensitivity of initial salvage price to the final salvage price

6.3.2.4 Sensitivity of discount rate

The choice of the discount rate has an impact on the estimation of the total salvage value in each of the model years. The sensitivity of the discount rate, as calculated from average interest rates in the past 7 years, has been tested in the district of Schwarzwald-Baar-Kreis, with a minimum value of 2% to a maximum of 8%, with an equal step, which leads to 4 simulation runs. With an annual discount rate of 2%, the net present value of the total salvage to be sold over the next 5 years is approximately 193 million Euros, and with a discount rate of 6% and 8% per annum, the value is 183 and 179 million Euros, respectively. The influence of varying discount rates on the net present salvage values of different model years is shown in Figure 6.10.

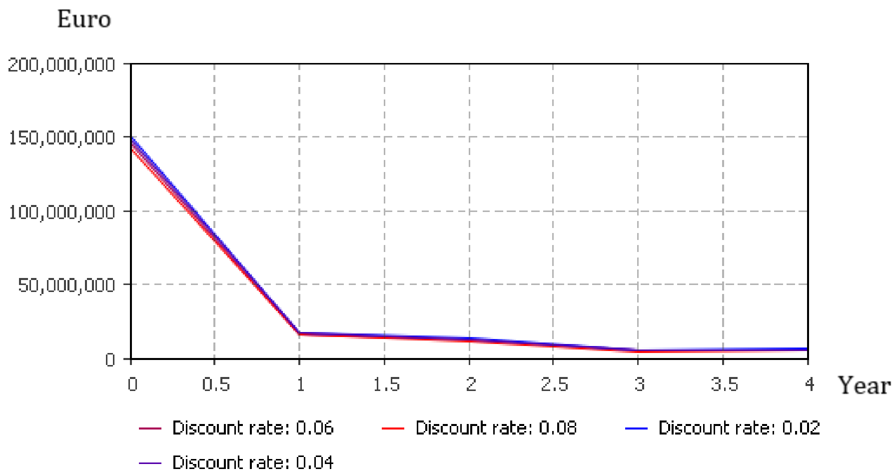

Figure 6.10: The sensitivity of final salvage value in the district of Schwarzwald-Baar-Kreis in relation to the discount rate

In assessing the net present value of the costs associated with forest clearing areas, it is observed that the consideration of a higher discount rate would considerably reduce the total costs calculated for the later model years. For instance, in the district of Schwarzwald-Baar-Kreis, a discount rate of 8% per annum, would result in a net present value of the aggregated costs of different model years in forest clearing areas to around 542 million Euros, compared to 672 million Euros at a 2% annual discount rate (Figure 6.11).

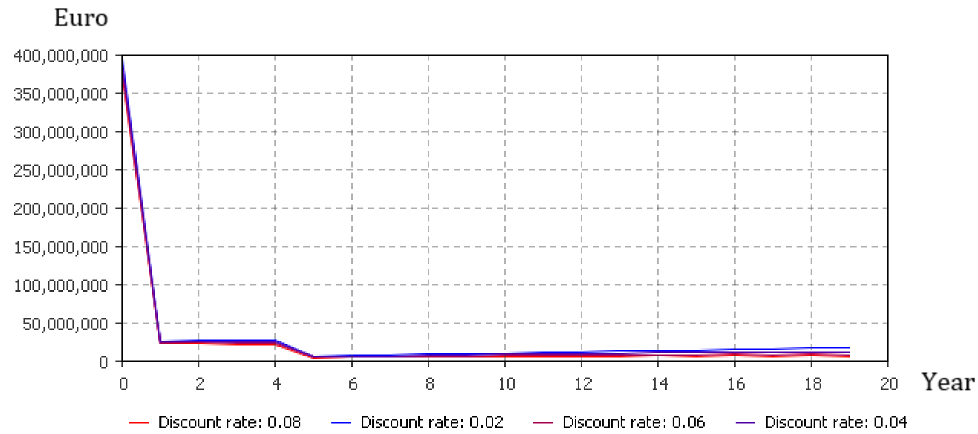

Figure 6.11: The sensitivity of forest clearing area value in the district of Schwarzwald-Baar-Kreis in relaion to the discount rate

6.4 Summary and outlook

Two scenarios are proposed in this chapter. The immediate salvage operation proves profitable, compared to the reference scenarios and delayed salvage operation.

The selection of appropriate policies is extremely important as the simulated economic impacts of storm vary according to the policies chosen. Policies defined in this study are considered for all the districts in Baden-Württemberg. Additional scenarios can be built considering the public or private forest owners' decisions on forest management and the conditions in different districts. In reality, each district would experience different circumstances after the storm, therefore, a selection of district or region specific policies, and an evaluation of their impacts would be beneficial.

Furthermore, a simple causal reasoning (based on cause and effect) on a feedback system is difficult (Åström & Murray, 2008) and complex. Therefore, it is important to analyse the system as a whole. Some sensitivity analyses were also performed to identify the effect of some of the most important parameters (i.e. causes) on model outcomes (i.e., effects). The price elasticity of demand and the discount rate proved critical to the model outcome.

All the model parameters in this research are justified through a comprehensive literature review (see Section 2.3.4), yet some of them are subject to higher uncertainty. For example, to assume a current low discount rate to be continued in the following years, would have a significant influence on the assessment of net economic impact. Therefore, further sensitivity analyses would also help to improve the understanding of the behaviour of submodels and the overall system modelled.

7 Aggregation of Results and Outlook

7.1 Summary of the study

7.1.1 Summary of research objective

Forestry is of paramount importance to the state of Baden-Württemberg, as it supplies wood resources for material and energetic use, and plays a central role in energy transition, climate protection, etc. On the other hand, Baden-Württemberg has been and will might hit by extreme winter storms that significantly damage the forest resources and wildlife habitat, as well as roads and infrastructure. Such storms may occur with greater intensity and more frequently than before, which might cause increased associated costs.

The identification of the vulnerability of forest resources to extreme storms and the assessment of the related economic impact are very complex. Both require highly detailed sets of multi-sectoral data, a robust modelling approach, as well as consideration of the spatial and temporal aspects, dynamics and interactions of different factors associated with forestry, markets and management decisions. To address these challenges, two models are developed in this research (Figure 1.14).

The first model 'Weight of Evidence (WofE)' is based on a combined GIS and statistical analyses to identify the posterior probability maps of vulnerable forest areas in the state of Baden-Württemberg in Germany. The outcome of the WofE model is used as an input into a system dynamics model - which is based on a dynamic feedback structure and economic theories - to evaluate the economic impacts due to a particular event, considering different forest management and salvage operation decision options. The model is able to demonstrate the changes in impacts over time across all the districts, as the model components constantly evolve due to previous feedback actions and conditions. A decision support tool is also developed to simulate the impact of alternative management strategies.

7.1.2 Summary of vulnerability analysis

In analysing the vulnerability, forest resources and forest management practices with reference to the state of Baden-Württemberg are primarily explained in **Chapter 2**. In this regard, a statistical overview of the forest resources, use and flow of wood resources, forest management before and after extreme storms, as well as various statistical data and assumptions are described.

Later, the wind effects on trees and a comprehensive literature review on the assessment of storm damage, factors of windthrow and related windthrow modelling approaches in different geographic extents and scales are illustrated in **Chapter 3**.

The empirical WofE model is found to be a suitable approach to analyse the vulnerability of forest resources in Baden-Württemberg. Different steps associated with this approach are systematically described; multiple model outcomes are evaluated and validated in order to justify the acceptance of the posterior probability maps of the vulnerable forest areas in Baden-Württemberg. In this regard, 11 different models with varying combinations of predictor variables (evidence themes) are tested to understand the most important variables.

The most significant model (M8) uses 3,221 known windthrow affected areas as training points in conjunction with four evidence themes, i.e., soil type, forest type, topographic exposure in direction of west and gust wind speed greater than 35 m/s to produce the posterior probability maps of windthrow vulnerability - at a raster grid with cells in a one ha unit area - in the state of Baden-Württemberg. Posterior probabilities are calculated for approximately 14 million ha of forests. A classification reveals that majority of the forests (62%) are within the lowest damage class. The moderate damage probability class covers 20%, and the highest damage probability class covers 18% of the area (Figure 3.7). The probability values are highest in the west, where topographic exposure values are at a maximum, soil is acidic and forests are coniferous. The districts of Calw, Freudenstadt. Breisgau-Hochschwarzwald, Ortenaukreis, Schwarzwald-Baar-Kreis are found to be the most vulnerable districts in Baden-Württemberg.

The outcome of the WofE model is used to investigate windthrow probability and is meant to provide scientists and policy makers with a state-wide perspective of expected damage patterns of different magnitudes, considering the present conditions. Moreover, with the delineation of areas with different vulnerabilities, economic impacts can be analysed and evaluated considering typical post storm forest management and salvage operation practices.

7.1.3 Summary of economic impact assessment

In assessing economic impacts, the theoretical framework needed to assess the impacts of extreme winter storms on forest resources is at first thoroughly discussed in **Chapter 4**. The different conditions after winter storms - such as economics of salvage decisions, market behaviour and their characteristics - are explained. The system dynamics model proves to be a suitable approach to assess the impacts. Its components and application in the field of economic and spatial modelling, as well as its limitations and advantages are described.

In **Chapter 5**, the combined spatial and system dynamic based economic model is formulated. Five submodels (Figure 5.1) are developed to assess the values related to salvage, standing timber and forest clearing areas. A model boundary chart, a subsystem diagram and causal loop diagrams are prepared to explain the scope and dependencies of different parameters and the feedback structures of the submodels. Finally, stock and flow diagrams and related input data are explained to illustrate the reference simulation runs in the districts of Baden-Württemberg.

The reference simulation runs illustrate the main characteristics of the model behaviour, aiming to promote understanding of the dynamic properties of the multidimensional and interdisciplinary aspects of the model. Since different districts accommodate varying forest resources, they are impacted differently by the stochastic storm. The model is also validated with a set of structural and behavioural tests, as suggested by the system dynamics literature and best practices.

The salvage price submodel dynamically determines the salvage price in the state of Baden-Württemberg in each simulation run, considering the initial reference salvage price, price adjustment time, reference supply, demand, and their elasticities. During the first three years, prices decline, e.g., from 55 to 21 Euro/m^3 but then grow again to 32 Euro/m^3 in the fifth year. The forest clearing area and standing timber value submodels are run in all districts in Baden-Württemberg over 20 years. The pre-storm timber value submodel illustrates the pre-storm conditions in all these districts, assuming that another extreme storm would not occur.

The outcome of the reference simulation runs of different submodels can be used to understand how individual districts might become economically vulnerable or adversely, gain from the effects of an extreme storm.

In **Chapter 6**, two policy based scenarios are formulated to identify the impacts of alternative forest management and salvage operation strategies. The immediate salvage operation proves profitable, compared to the reference scenarios and delayed salvage operation. For example, in the district of Schwarzwald-Baar-Kreis, the net present value of the discounted salvage is higher in the immediate salvage operation policy (226 million Euros), than in the reference scenario (187 million Euros), and in the delayed salvage operation policy (77 million Euros). However, the delayed salvage operation policy offers environmental and ecological benefits which are difficult to quantify in terms of monetary values.

Finally, four sensitivity analyses are performed to identify the impact of some of the most important parameters on model outcome. The price elasticity of demand proved critical to the final salvage price, as a small variation of elasticity leads to a larger change in final salvage price. For example, an increase of demand elasticity from -0.5 to +0.5, reduces the salvage price by 67% in the fourth year, and a decrease of elasticity to -1 increases the price by 20%. The discount rate also proves to be highly critical in assessing values related to forest clearing area or standing timber, as it runs over 20 years. It is less important in assessing the salvage price which runs for 5 years.

By studying the possible future impacts of an extreme winter storm, forest managers and private forest owners are able to prepare marketing strategies in order to control the sale of salvage timber, prevent the depreciation of its value, reduce unintended economic loss or plan sustainable forest management. Assessing the net value (considering the positive and negative cash flows) is critical, since the total cost related to forest clearing areas, salvage operation as well as the value of the wood, is tied up for a prolonged period of time, potentially leading to a heavy economic loss in some districts.

Proposed system dynamics approach - with its scalability in terms of time and space - provides an important basis to evaluate the impacts in forestry. It can be applied to both operational challenges and policy analysis, as well as the exploration of possible future scenarios.

7.2 Limitation and open research questions

Both WofE and system dynamics models demonstrate some limitations regarding their methodological approaches, assumptions and input datasets. The most important limitations and open research questions are highlighted in this section.

The accuracy of the estimation of impacts may not be the most important concern, since extreme events differ from conventional events. Each event is unique, and exactly the same hazard will never occur twice. Hence, the impact analysis of extreme events is not a forecast of an event or of its consequences; rather, it suggests only what might happen. As (Hewings & Mahidhara, 1996) wrote, disaster impact analysis is an ‘inexact science’. Therefore, future research should endeavour to improve the accuracy of the model results.

Simulated wind speeds were not the most significant predictor for assessing the vulnerability of forest resources in the WofE model. This is in agreement with other studies which have investigated windthrow damage in central Europe (Schütz et al., 2006), (Schindler, Grebhan, et al., 2012), (Albrecht et al., 2012). The severity of damage also depends on the duration of the event, maximum sustained wind speed and precipitation immediately prior to and during the event (Mitchell, 2012). Therefore, further investigation on understanding the interaction of these factors over the duration of a storm is required.

The probabilities of WofE model are influenced by weights based on area proportions; thus, when classes of the evidence themes cover small areas and there is a high proportion of damage, the calculated weights for these classes will carry more influence. Subdividing into smaller areas and performing WofE for each area would improve the results for similar regions with an increase in classes. When assessing smaller areas, weights for site variables will then be less influenced by training points in distant locations with different topography and site conditions. For example, soil type layer was classified by general soil types resulting in 29 classes; classification based on specific soil units of the soil layer (354 classes) would allow delineation of smaller areas and assessment of their spatial association to damage. This way, the WofE methodology can be improved in future.

This research assumes a stochastic winter storm which affects all the districts in Baden-Württemberg. But in reality, the extent of the storm might be smaller or vice versa. For example, Lothar affected some regions in Baden-Württemberg, especially in the Black Forest, but not the whole of Baden-Württemberg. Therefore, future research could focus on smaller regions and inspect the vulnerability with higher resolution of data. For example, forest establishment (*Forsteinrichtung*) data[1], which contains detailed tree and stand information for the public forests in Baden-Württemberg, can be explored.

The modelling efforts presented in this research are not final. System dynamics is an iterative approach (Sterman, 2000) and by far, not all scenarios are analysed in this research. The proposed model comprises 35 variables; and is developed into the graphical and mathematical representation of interactions, governing the behaviour of the complex forest system immediately after an extreme storm. The system dynamics model and the related data could be further investigated

[1] http://forstbw.de/schuetzen-bewahren/waldinventur/forsteinrichtungen.html.

considering the contemporary evolution of the forestry sector, especially regarding the salvage market and discount rates.

Temporary storage of salvage is not included in the modelling. Since the establishment of storage sites is costly, this might reduce the positive cash flows from selling the salvage. The benefits of maintaining the quality of salvage in storage facilities and thus avoiding sudden price reductions immediately after the storm could be studied in future. Moreover, using the GIS, the location of potential storage sites can be identified.

The rate of deterioration of salvage quality varies among the tree species. True heartwood species (e.g., Oaks) often have good keeping ability without the need to take any precautions, whereas sapwood species (e.g., Maple) require immediate actions (Pischedda, 2004). Such variations of deterioration rates among species types are not reflected in this research.

The impacts modelled in this research can be measured by market values. The non-market losses are difficult to estimate and require comprehensive modelling techniques. For example, loss of leisure, space or historical monuments and government services could be assessed by contingent valuation techniques, but such techniques have yet to be employed (Cochrane, 2004). Preliminary evidence suggests that the non-market economic impacts of forest disturbances are substantial (T. P. Holmes et al., 2008b). Thus future studies should focus on the assessment of non-market value.

Instead of generalised input values for trees, the system dynamics model can be enriched by considering separate input parameters associated with the coniferous and deciduous trees. For example, the price setting of coniferous and deciduous trees could be modelled separately, since their prices are different. The price elasticities of demand and supply (and other model parameters) are also different, therefore, the setting of the final salvage price for coniferous and deciduous trees would be more accurate.

7.3 Outlook

The modelling framework developed in this research is based on the empirical evidences from the forest management practices in the state of Baden-Württemberg. The framework can serve to build individual scenarios as the model parameters are scalable in terms of time and space – i.e., they can be adapted to other regions and time scales - and they can be further improved, with more detailed data and input parameters. It can be further extended to analyse the micro-economic and environmental impacts across the forestry sector with or without evaluating the regional and macro-economic impacts. For instance, the impacts on energy price or wood based products, etc. could be investigated.

Public authorities still lack appropriate decision support tools for evaluating their strategic decisions in the aftermath of a storm (Riguelle et al., 2015). In this research, a decision support tool is developed to help the forest managers (federal or state) and private forest owners to understand the impact of extreme winter storms on forest resources, as well as to evaluate the impact of their decisions regarding forest management and salvage operation (**Appendix 6**). They can use this tool multiple times, with different assumptions on market conditions or other input data, to simulate different management scenarios (e.g., profit oriented, ecologically oriented, etc.) and to optimize their forest management plan for ten years and more.

The delineation of vulnerable forest areas and associated economic impacts due to extreme storms gives a comprehensive insight into the conditions of the districts. This study would aid the decision-makers to formulate risk management strategies for individual districts. Stakeholders from both public and private forests could be involved to ensure the development of these strategies and their applicability. Therefore, future research should explore and expand the local adaptation and mitigation strategies to respond to the range of impacts that may occur, in order to reduce the vulnerability of forests due to extreme winter storms.

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Appendices

Appendix 1: Description of the Weight of Evidence modelling software and configuration steps

ESRI ArcGIS 10 and its Spatial Analysis Extension are used for pre-processing the data (ESRI, 2014). WofE methodology environment is included in the Spatial Data Modeller Extension (ArcSDM) for ArcGIS 10, and is publicly available from ArcGIS resources centre (Sawatzky, Raines, & Bonham-Carter, 2010). The extension is designed to perform several mathematical techniques, e.g., weights of evidence, logistic regression, neural network methods, fuzzy logic etc. This study utilized the 'Weights of Evidence' and 'Utility' scripts to identify areas where windthrow is likely to occur based on evidence provided by GIS layers. Additionally, the open source GIS software GRASS (GRASS, 2012) is also used to calculate distance-limited TOPEX indices for evidence layers in the model.

The Arc-SDM toolbox has certain preconditions and settings that must be set before running the model. For environment settings, 'Workspace' and 'Scratch workspace', extent, cell size, analysis mask, and output coordinate systems are required when using this toolbox. Because the toolbox is not capable of projecting on the fly, all layers must have a common reference system and this must be set in ArcGIS Environments. Furthermore, the tool assumes that all calculations are made with spatial units of metres.

Unit cell area is a term used in ArcSDM modelling that refers to the area in which a single training point is assumed to occupy. The calculations in WofE result in a probability of a unit cell containing a training point. This value is independent of the resolution of the input and output, rather it represents the size of an area in which wind damage is likely to occur. The unit cell size in this model is set to one ha (corresponding to approximately 11 pixels at 30 metres resolution).

Appendix 2: Description of data and harmonization steps

Different types of geographical and statistical data on forestry, environment and weather are required to assess the vulnerability of forest resources in Baden-Württemberg (Table 14). These datasets having different temporal, spatial and content related resolutions are gathered to use as evidence information in the form of GIS layers to apply the WofE methodology. For this reason, several geoprocessing tasks are applied to harmonize (common reference system, uniform format, extent, etc.) the data and later to fit to the WofE model. A description of the data selection process for this research as well as their harmonization procedures is given here.

Table 14: An overview of the characteristics of required data for the WofE model

Data	Type of data	Description	Source
LUBW Land use 1975, 1993, 2000 and 2010	Raster (Grid)	Forest type, windthrow 30 m × 30 m	(LUBW, 2011)
CORINE[1] Land Cover 1990, 2000, 2006	Vector, Raster (Grid)	100 m × 100 m	(Keil et al., 2005), DLR[2]
Extreme winter storm hazard, 1971 - 2000	ASCII file	Maximum mean wind speed for different return periods, 1 km × 1 km	(Hofherr & Kunz, 2010)
Water and Soil Atlas of Baden-Württemberg (WaBoA)	Vector (Feature class)	Geophysical condition - Geology, water, soil. Scale of 1: 200,000	(WaBoA, 2004)
SRTM[3] Digital Elevation Model	Raster (Grid)	90 m × 90 m	(USGS, 2012)

- **Land use/cover and storm damage data**

Land use/cover datasets are useful for obtaining basic information such as forest type, areas, etc. for the entire state of Baden-Württemberg. The raster land cover dataset from LUBW has a spatial resolution of 30 metres and is available for 1975, 1993, 2000, and 2010 (LUBW, 2011). The CORINE Land Cover data (CLC) is also available from the DLR (Keil et al., 2005), either in raster or vector format, at a 100

[1] Coordination of Information on the Environment.
[2] Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center).
[3] Shuttle Radar Topography Mission.

metres spatial resolution for 1990, 2000, and 2006[4]. Both datasets contain forest coverage classes for coniferous, deciduous, and mixed forests.

The proposed WofE method requires forest condition data prior to an extreme storm. For this purpose, both CLC 1990 vector dataset and LUBW 1993 raster datasets can be used. The 30 metre resolution of the LUBW dataset allows for a precise differentiation between the different forest classes when compared with the CLC data. Moreover, the spatial and temporal resolution of the LUBW land cover 1993 dataset makes it the best candidate for depicting forest conditions prior to a storm (e.g., Lothar in 1999). The spatial analysis of the dataset reveals that the total forest area is approximately 14,109 Km^2, with coniferous trees covering 7,700 Km^2 (55%), deciduous 2,795 Km^2 (20 %), and mixed 3,614 Km^2 (25%) as illustrated in Figure A. 1.

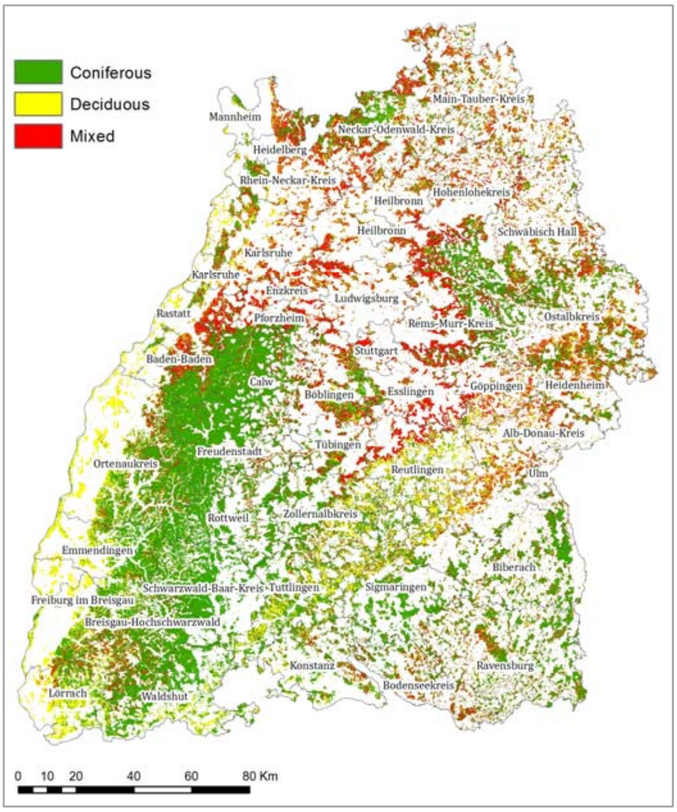

Figure A. 1: Three types of forest cover in Baden-Württemberg (LUBW 1993 dataset)

- **Storm damage data**

Both LUBW and CLC datasets contain information on windthrow damaged areas for certain years. For example, in LUBW data, the years 2000 and 2010 contain a class

[4] http://www.corine.dfd.dlr.de/datadescription_2006_de.html.

of 'windthrow' (*windwurf*, class 139). For CLC data, the years 2000 and 2006 contain a class, 'transitional woodland – shrub' (CLC class 324), which represents areas damaged by the winter storm Lothar in 1999 (Keil et al., 2005).

Both CLC and LUBW land cover datasets, available from the year 2000, contain damage information. The CLC windthrow class covers approximately 3% of the total forested area and LUBW covers approximately 2% of the total forested area. (Dirk Schindler et al., 2009) noted that the minimum detection size of windthrow areas for CLC data was 5 ha (50,000 m^2), while LUBW is capable of delineating windthrow areas as small as 30 m^2. The difference in spatial resolutions between the two datasets is illustrated in Figure A. 2.

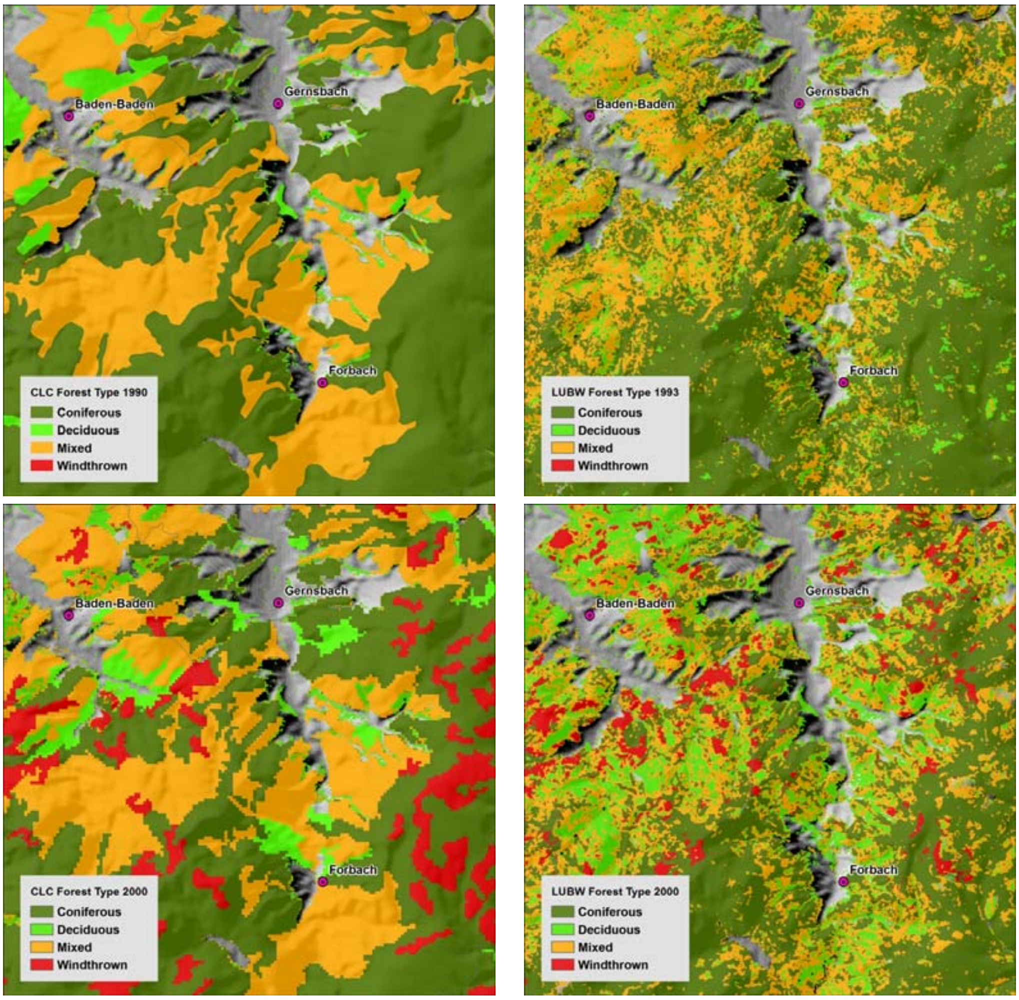

Figure A. 2: Land cover datasets from CLC 1990 (upper left), CLC 2000 (lower left), LUBW 1993 (upper right) and LUBW 2000 (lower right)

The share of deciduous, coniferous, mixed and windthow classes within the CLC and LUBW dataset is presented in Table 15.

Table 15: Characteristics of CLC and LUBW land cover data

Dataset	**Percent of total area forested area**			
	Deciduous (311 or 140)	Coniferous (312 or 130)	Mixed (313 or 150)	Windthrow (324 or 139)
CLC 1990	20.6	43.72	35.68	N/A
LUBW 1993	19.82	54.56	25.62	N/A
CLC 2000	20.4	41.42	35.15	3.01
LUBW 2000	30.3	32.57	35.00	2.1
CLC 2006	20.35	41.63	35.47	2.56
LUBW 2010	17.46	36.53	44.81	1.2

The visual inspection using Google Earth reveals that the LUBW 2000 land cover data, in many cases do not classify all damaged areas present in CLC 2000 and vice versa. Therefore, further steps are taken to combine the two datasets containing damaged areas. But even after their combination (Figure A. 3), some forested areas that are windthrow by the winter storms of Lothar and Martin, are not displayed spatially. This signifies the limitation of the data sources[5].

Therefore, the training points are derived from LUBW 2000 and CLC 2000 damage classes under the condition that the damage areas are greater than one ha which leads to a total number of 3,221 training points.

[5] No further step is taken to include these missing damage areas because of the complicacy regarding correcting these datasets at an extent such as the State of Baden-Württemberg.

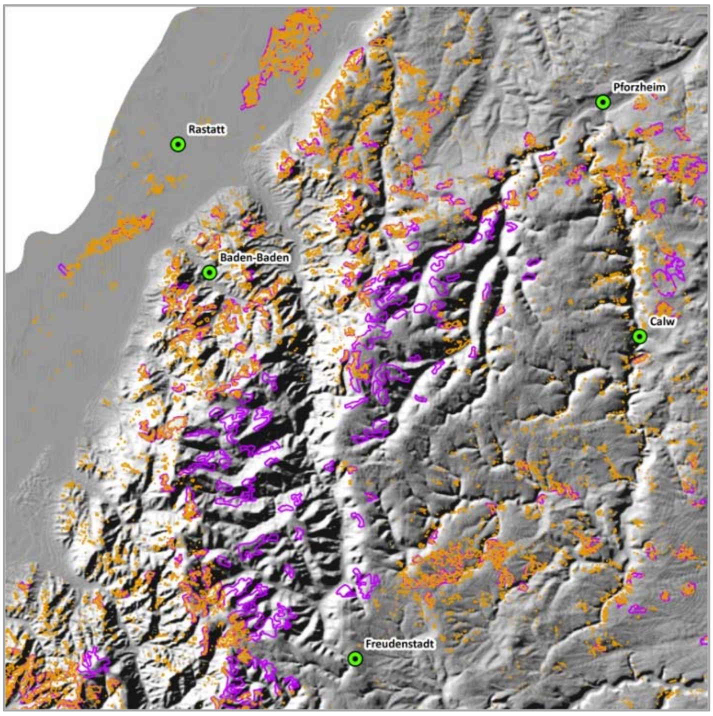

Figure A. 3: Visualization of LUBW 2000 (orange polygons) and CLC 2000 (purple polygons) damage datasets

- **Extreme winter storm hazard data**

Spatially highly resolved wind fields of severe storm events in the climatological period from 1971 to 2000 are available at the IMK-KIT (Heneka, 2006; Hofherr & Kunz, 2010). This data is modelled by a statistical-dynamical downscaling approach with the Karlsruhe Atmospheric Mesoscale Model (KAMM) to assess the local hazard caused by large-scale winter storms (Hofherr & Kunz, 2010).

The hazard maps reveal critical regions with potentially extreme wind speeds depending on exposure, terrain height and land use. A major assumption of the KAMM model is that the resulting wind fields represent the maximum mean velocities of each individual simulated storm event (Hofherr & Kunz, 2010). The simulated storm events derived from this process are gust wind fields at a 1 km^2 resolution covering the entire state of Baden-Württemberg for return periods of 5, 10, 20, 50 and 100 years.

This data is collected as an ASCII text file containing the maximum mean wind speed in metres per second over ten minutes at 1 km^2 spatial resolution with a projected coordinate system of UTM zone 32. The ASCII file is converted to a float raster grid with a projection of Gauss Kruger zone 3 in ArcGIS. Gusts with the highest wind speeds can be observed in mountainous areas throughout the Black Forest and along the northern sections of Swabian Mountains (*Schwäbische Alb*), while the lowest values are located in deep valleys in the Black Forest and the northeast region of the state as portrayed in Figure A. 4.

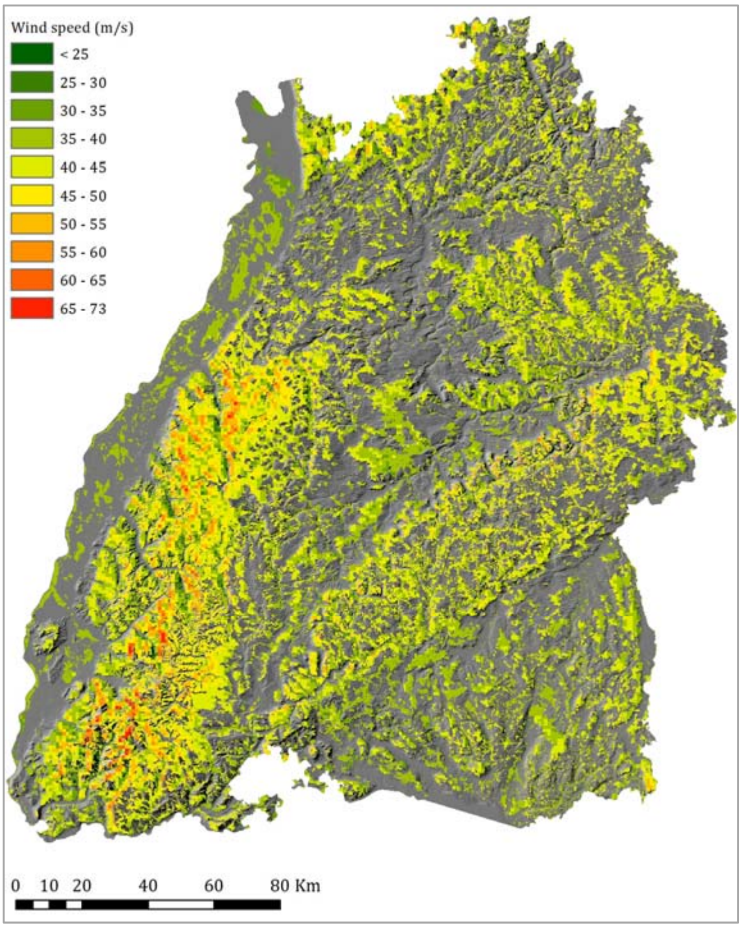

Figure A. 4: Simulated maximum wind speeds in Baden-Württemberg on a 1 km × 1 km grid with an exceedance probability of p = 0.01 (mean return periods of 100 years)

- **Soil data**

The most important physiographic conditions in Baden-Württemberg are represented in the Water and Soil Atlas of Baden-Württemberg (WaBoA, 2004). This vector dataset covers the entire study area of Baden-Württemberg at a scale of 1: 200,000. The most important variables required as evidence layers in the WofE method are soil type (29 classes), soil moisture (21 classes), soil acidity (13 classes), and geology (14 lithostratigraphic units).

- **Elevation data**

NASA's Shuttle Radar Topography Mission (SRTM) dataset is used as elevation data and is extracted from the USGS EarthExplorer portal (USGS, 2012). The 90 metre resolution (3 arc second) elevation data covering the entire study area of Baden-Württemberg is comprised of eleven geoTIFF files, each covering one degree of latitude and longitude with a projection system of WGS 1984.

The eleven geoTIFF files were combined into one seamless raster dataset with the Gauss Kruger zone 3 projection and 76.857 square metre cell (Figure A. 5). The elevation data is used to calculate elevation, slope, aspects and topographic exposure (TOPEX)[6] of the study area of Baden-Württemberg.

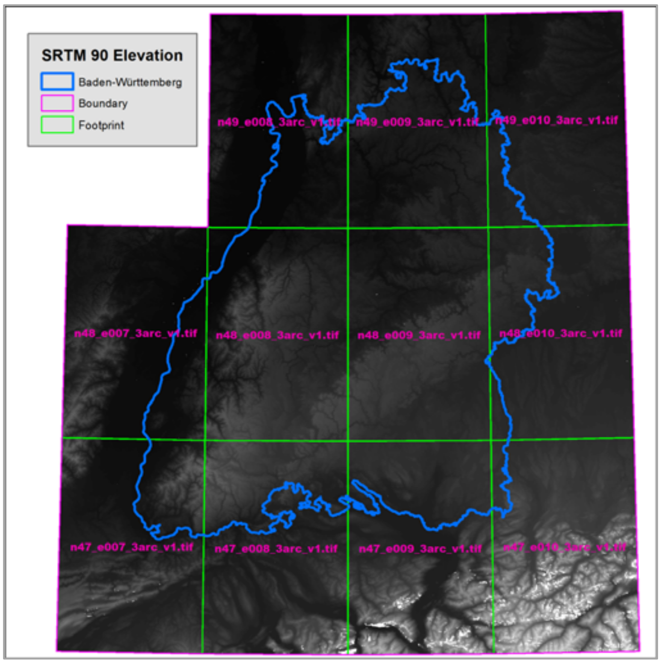

Figure A. 5: Raster mosaic of eleven SRTM tiles covering the entire state of Baden-Württemberg

[6] Topographic exposure is a topographic characteristic representing a degree of protection by a surrounding topography of a certain site (Mikita & Klimánek, 2010).

Appendix 3: Results of the statistical analysis of evidence themes

A. Soil acidity evidence theme

Soil acidity												
Class	**# TPs**	**Area (Km^2)**	**W+**	**σW+**	**W-**	**σW-**	**Contrast C**	**Cσ**	**Stud(C)**	**GEN_Class**	**Weight**	**Weightσ**
10	1080	4268.7738	0.1237	0.0305	-0.0593	0.0221	0.183	0.0376	4.8652	10	0.1237	0.0305
11	1057	2452.2282	0.6583	0.0308	-0.219	0.0219	0.8774	0.0378	23.1901	11	0.6583	0.0308
12	172	656.0361	0.1595	0.0763	-0.0085	0.0184	0.168	0.0785	2.1392	12	0.1595	0.0763
13	496	2253.3066	0.0158	0.045	0.003	0.0195	-0.0188	0.049	-0.3835	99	-0.020081	0.043403
14	121	1471.0347	1.0015	0.0909	0.0716	0.0182	-1.0731	0.0928	-11.5691	14	-1.0015	0.0909
15	121	1330.6977	0.9012	0.091	0.0604	0.0182	-0.9616	0.0928	-10.3667	15	-0.9012	0.091
30	35	166.2147	0.0602	0.1692	0.0007	0.018	-0.0609	0.1702	-0.3582	99	-0.020081	0.043403
40	1	7.6914	0.5432	1.0007	0.0002	0.0179	-0.5435	1.0008	-0.543	99	-0.020081	0.043403
41	7	238.4757	2.0325	0.378	0.0149	0.0179	-2.0474	0.3784	-5.4101	41	-2.0325	0.378
42	18	287.4177	1.2744	0.2358	0.015	0.0179	-1.2893	0.2365	-5.4527	42	-1.2744	0.2358
43	15	394.3854	1.7733	0.2582	0.0238	0.0179	-1.7971	0.2589	-6.9421	43	-1.7733	0.2582
44	4	268.056	2.7092	0.5	0.018	0.0179	-2.7272	0.5004	-5.4505	44	-2.7092	0.5
45	12	243.0585	1.5123	0.2887	0.0137	0.0179	-1.526	0.2893	-5.2747	45	-1.5123	0.2887

B. Soil moisture evidence theme

Soil moisture												
Class	**# TPs**	**Area (Km²)**	**W+**	**σW+**	**W-**	**σW-**	**Contrast C**	**Cσ**	**Stud(C)**	**GEN_Class**	**Weight**	**Weightσ**
1	3	178.785	-2.5903	0.5774	0.0118	0.0178	-2.6021	0.5777	-4.5044	1	-2.5903	0.5774
2	78	425.0124	-0.1964	0.1133	0.0055	0.0181	-0.202	0.1148	-1.7598	199	-0.014395	0.024675
3	112	823.1679	-0.4962	0.0946	0.024	0.0182	-0.5201	0.0963	-5.4019	3	-0.4962	0.0946
4	262	1222.6545	-0.0411	0.0618	0.0038	0.0186	-0.045	0.0646	-0.6961	199	-0.014395	0.024675
5	326	1927.7703	-0.2784	0.0554	0.0378	0.0188	-0.3161	0.0585	-5.3999	5	-0.2784	0.0554
6	302	1128.4767	0.1816	0.0576	-0.0175	0.0188	0.1991	0.0606	3.2854	6	0.1816	0.0576
7	356	1612.9539	-0.0115	0.0531	0.0015	0.0189	-0.013	0.0563	-0.231	199	-0.014395	0.024675
8	881	3916.0683	0.0076	0.0337	-0.0029	0.021	0.0106	0.0397	0.2655	199	-0.014395	0.024675
9	44	194.7672	0.0118	0.1509	-0.0002	0.018	0.012	0.152	0.0787	199	-0.014395	0.024675
10	27	300.9024	-0.9129	0.1925	0.013	0.0179	-0.9259	0.1934	-4.7882	10	-0.9129	0.1925
11	1	41.5917	-2.2305	1.0001	0.0026	0.0178	-2.2332	1.0003	-2.2325	11	-2.2305	1.0001
12	11	172.0638	-1.2522	0.3016	0.0088	0.0179	-1.261	0.3021	-4.1735	12	-1.2522	0.3016
13	60	168.7257	0.4668	0.1293	-0.0072	0.018	0.474	0.1306	3.63	13	0.4668	0.1293
14	113	188.2521	0.9928	0.0944	-0.0232	0.0182	1.0159	0.0961	10.5728	14	0.9928	0.0944

C. Soil type evidence theme

Soil type												
Class	**# TPs**	**Area (Km^2)**	**W+**	**σW+**	**W-**	**σW-**	**Contrast C**	**Cσ**	**Stud(C)**	**GEN_ Class**	**Weight**	**Weightσ**
99	0	0.2511	0	0	0	0	0	0	0	299	-0.001876	0.030435
100	8	60.1029	-0.5169	0.3538	0.0017	0.0179	-0.5187	0.3542	-1.4642	299	-0.001876	0.030435
101	54	194.6988	0.2186	0.1363	-0.0034	0.018	0.2221	0.1375	1.6156	299	-0.001876	0.030435
102	16	42.1587	0.5333	0.2505	-0.0021	0.0179	0.5354	0.2511	2.1321	102	0.5333	0.2505
103	2	57.2085	-1.8549	0.7072	0.0034	0.0179	-1.8583	0.7075	-2.6267	103	-1.8549	0.7072
104	5	42.192	-0.6333	0.4475	0.0014	0.0179	-0.6347	0.4478	-1.4172	299	-0.001876	0.030435
105	17	235.5471	-1.1296	0.2426	0.0114	0.0179	-1.1411	0.2433	-4.6904	105	-1.1296	0.2426
106	266	847.7649	0.3424	0.0614	-0.0264	0.0187	0.3688	0.0642	5.7462	106	0.3424	0.0614
107	56	288.5922	-0.1394	0.1338	0.0027	0.018	-0.1421	0.135	-1.0528	299	-0.001876	0.030435
108	1	11.6073	-0.9524	1.0004	0.0005	0.0179	-0.9529	1.0006	-0.9524	299	-0.001876	0.030435
109	8	33.5124	0.0683	0.354	-0.0002	0.0179	0.0684	0.3544	0.1931	299	-0.001876	0.030435
110	0	2.9304	0	0	0	0	0	0	0	299	-0.001876	0.030435
111	0	1.9539	0	0	0	0	0	0	0	299	-0.001876	0.030435
112	4	143.9487	-2.0845	0.5001	0.009	0.0179	-2.0936	0.5004	-4.1839	112	-2.0845	0.5001
201	481	2056.563	0.0478	0.0456	-0.0084	0.0194	0.0561	0.0496	1.1318	299	-0.001876	0.030435
202	16	186.5466	-0.9569	0.2501	0.0082	0.0179	-0.9651	0.2507	-3.849	202	-0.9569	0.2501
203	309	625.4721	0.7981	0.057	-0.0582	0.0188	0.8563	0.06	14.2605	203	0.7981	0.057
204	506	1688.0967	0.2965	0.0445	-0.048	0.0195	0.3445	0.0486	7.0893	204	0.2965	0.0445
205	72	206.0298	0.4505	0.1181	-0.0085	0.0181	0.4589	0.1194	3.8428	205	0.4505	0.1181
206	299	1329.3666	0.0086	0.0579	-0.0009	0.0188	0.0095	0.0609	0.1556	299	-0.001876	0.030435
207	105	543.6711	-0.1441	0.0977	0.0054	0.0182	-0.1495	0.0994	-1.5045	299	-0.001876	0.030435
208	65	295.6059	-0.0141	0.1242	0.0003	0.018	-0.0144	0.1255	-0.1148	299	-0.001876	0.030435
209	198	672.642	0.2783	0.0712	-0.0162	0.0184	0.2945	0.0735	4.006	209	0.2783	0.0712
210	3	87.0795	-1.8695	0.5774	0.0052	0.0179	-1.8748	0.5777	-3.2451	210	-1.8695	0.5774
211	2	50.4882	-1.7299	0.7072	0.003	0.0179	-1.7328	0.7075	-2.4493	211	-1.7299	0.7072
301	332	1149.255	0.2595	0.055	-0.0266	0.0189	0.2861	0.0581	4.9234	301	0.2595	0.055
302	88	636.4242	-0.4788	0.1067	0.0178	0.0181	-0.4966	0.1082	-4.59	302	-0.4788	0.1067
303	191	2295.9351	-0.9875	0.0724	0.1153	0.0184	-1.1027	0.0747	-14.7631	303	-0.9875	0.0724
401	42	321.7995	-0.5366	0.1544	0.0097	0.018	-0.5463	0.1554	-3.5142	401	-0.5366	0.1544

D. Geology evidence theme

Geology												
Class	# TPs	Area (Km^2)	W+	σW+	W-	σW-	Contrast C	Cσ	Stud(C)	GEN Clas s	Weight	Weight σ
1	101	533.808	-0.1653	0.0996	0.006	0.0181	-0.1713	0.1012	-1.6916	99	-0.075946	0.03876
2	759	2327.1516	0.3806	0.0364	-0.0959	0.0205	0.4765	0.0417	11.4183	2	0.3806	0.0364
3	250	1155.4902	-0.0309	0.0633	0.0027	0.0186	-0.0336	0.066	-0.5095	99	-0.075946	0.03876
4	101	671.22	-0.3947	0.0996	0.0162	0.0181	-0.4109	0.1012	-4.0597	4	-0.3947	0.0996
5	29	604.8009	-1.5394	0.1857	0.0347	0.0179	-1.574	0.1866	-8.4352	5	-1.5394	0.1857
6	94	322.1784	0.2689	0.1033	-0.0072	0.0181	0.2761	0.1049	2.6327	6	0.2689	0.1033
7	705	2033.9721	0.4417	0.0377	-0.0981	0.0203	0.5398	0.0428	12.6054	7	0.4417	0.0377
8	280	644.5926	0.6683	0.0599	-0.0465	0.0187	0.7148	0.0627	11.3923	8	0.6683	0.0599
9	179	2029.8159	-0.9297	0.0748	0.0971	0.0184	-1.0268	0.077	-13.3344	9	-0.9297	0.0748
10	309	1480.5738	-0.067	0.0569	0.0076	0.0188	-0.0746	0.06	-1.2438	99	-0.075946	0.03876
11	253	1656.3546	-0.3797	0.0629	0.0412	0.0186	-0.4209	0.0656	-6.4155	11	-0.3797	0.0629
12	2	20.8638	-0.8462	0.7074	0.0008	0.0179	-0.847	0.7077	-1.1969	99	-0.075946	0.03876
13	79	584.4375	-0.5021	0.1126	0.0169	0.0181	-0.519	0.114	-4.552	13	-0.5021	0.1126
14	5	33.8202	-0.4124	0.4475	0.0008	0.0179	-0.4132	0.4479	-0.9225	99	-0.075946	0.03876

E. Gust wind evidence theme

Gust wind												
Class	**# TPs**	**Area (Km^2)**	**W+**	**σW+**	**W-**	**σW-**	**Contrast C**	**Cσ**	**Stud(C)**	**GEN_Class**	**Weight**	**Weight σ**
-99	36	111.9708	0	0	0	0	0	0	0	-99	0	0
1	1343	6761.3076	-0.1136	0.0273	0.0957	0.0238	-0.2093	0.0362	-5.7793	1	-0.1136	0.0273
2	1771	7235.3007	0.0957	0.0238	-0.1136	0.0273	0.2093	0.0362	5.7793	2	0.0957	0.0238

Appendix 4: Overview of the statistical summary of different models

Model name	Predictor themes used*	Observed windthrow TPs (n)	Expected windthrow occurrence s(T)	T-n	CI ratio (n/T)	AC test (T-n/σT)	Prob that model is not CI	Overall CI	AUC
M1	A, D, F, G, L, M, S,T	3221	6348.5	3127.5	0.51	31712519	1	0	0.74339
M2	A, F, G, L, M, S,T	3221	5409.7	2188.7	0.6	28610808	1	0	0.718925
M3	A, F, G, L, S,T	3221	4711.6	1490.6	0.68	22118812	1	0	0.709826
M4	A, F, G, L, M, T	3221	4092.9	871.9	0.79	16.885.709	1	0	0.716252
M5	F, L, M, S, T	3221	3569.1	348.1	0.9	8.818.192	1	0	0.693819
M6	A, F, G, L, T	3221	3731.9	510.9	0.86	9277636	1	0	0.715049
M7	A, F, L, M, T	3221	3503	282	0.92	6.159.362	1	0	0.710749
M8	A, F, L, T	3221	3295.2	74.2	0.98	1.415.498	0.922	0.157	0.705947
M9	F, L, S, T	3221	3311.9	90.9	0.97	205.169	0.98	0.04	0.688526
M10	G,F, L, T	3221	3270.4	49.4	0.98	1.071.215	0.858	0.284	0.696946
M11	F,L,M,T	3221	3241.7	20.70	0.99	0.419119	0.662	0.675	0.676524

*Here A is soil acidity, D is elevation in 6 classes (35-270, 270-420, 420-560, 560-720, 720-900, 900-1480 metres above sea level), F is forest type, G is geology, L is the gust wind speed > 35 m/s, M is soil moisture, S is soil type, and T is distance limited TOPEX for compass direction west. **M8 is selected as the most significant model.**

Appendix 5: List of parameters, variables, their description and units for different submodels

A. Salvage price submodel

Item	Description	Unit
P_{sl}	Salvage price	Euro/m^3
P_{slch}	Change in salvage price	Euro/m^3/year
IP_{sl}	Indicated price	Euro/m^3
PAT	Price adjustment time	year
D_{sl}	Demand	m^3
D_{ref}	Reference demand	m^3
P_{ref}	Reference price	Euro/m^3
ed	Demand elasticity	-
S_{sl}	Supply	m^3
V_{yasl}	Yearly available salvage volume	m^3
es	Supply elasticity	-
DS	Demand-supply balance	-
EDS	Effect of demand-supply balance on price	-
sen	Sensitivity of price to demand-supply balance	-

B. Salvage value submodel

Item	Description	Unit
V_{asl}	Available salvage volume	m^3
V_{tsl}	Total salvage volume	m^3
st	Stolen salvage percentage	%
re	Forest regeneration percentage	%
A_{af}	Affected area	Ha
av	Area to volume	m^3/ha
V_{yasl}	Yearly available salvage volume	m^3
se	Sell percentage	%
VA_{sl}	Salvage value	Euro
df	Salvage degradation factor	-
OC_{sl}	Salvage operation cost	Euro/m^3
C_l	Logging cost	Euro/m^3
C_o	Other cost	Euro/m^3
DVA_{sl}	Discounted salvage value	Euro
df	Discount factor	-
dr	Discount rate	%
dt	Discount time	year

C. Forest clearing area value submodel

Item	Description	Unit
C_{tp}	Tree plantation cost	Euro
C_p	Planting cost	Euro/ha
C_s	Plant secure cost	Euro/ha
V_{lt}	Potential loss of timber volume	m^3
ngr	Net timber growth rate	m^3/ha/year
V_{clt}	Change in potential loss volume	m^3/year
VA_{lt}	Potential loss of timber value	Euro
T_p	Timber price	Euro/m^3
VA_{fca}	Forest clearing area value	Euro

D. Standing timber value submodel

Item	Description	Unit
V_{st}	Standing timber volume in unaffected area	m^3
A_{uaf}	Unaffected area	Ha
fgr	Fractional growth rate	m^3/ha/year
ftr	Fractional thinning rate	m^3/ha/year
Gr	Growth rate	m^3/year
tr	Thinning rate	m^3/year
V_t	Timber volume	m^3
VA_{st}	Standing timber value	Euro
P_t	Timber price	Euro/m^3
C_h	Harvesting cost	Euro/m^3
C_o	Other cost	Euro/m^3

E. Pre-storm timber value submodel

Item	Description	Unit
VT_{pt}	Pre-storm timber Volume total	m^3
A_f	Forest area in district	Ha
V_{pt}	Pre-storm timber volume	m^3
VA_{pt}	Pre-storm timber value	Euro
V_{pt}	Timber price	Euro/m^3
P_{pct}	Change in timber price	Euro/m^3/year
P_{pa}	Adjusted price	Euro/m^3
se	Supply effect on price	-
VA_{pt}	Timber value	Euro
C_h	Harvesting cost	Euro/m^3
C_o	OtherCost	Euro/m^3
fgr	Fractional growth rate	m^3/ha/year
ftr	Fractional thinning rate	m^3/ha/year
Gr	Growth rate	m^3/year
tr	Thinning rate	m^3/year

Appendix 6: The graphical user interface of the decision support tool

A decision support tool is developed for the public and private forest owners to simulate different forest management scenarios and to evaluate the impacts of extreme winter storms on forest resources. The tool is able to run as a standalone application (without having installed the simulation software Anylogic) in any computer.

The Graphical User Interface (GUI) of the decision support tool is linked to the input files (Excel spreadsheet) for data access, where the users can choose alternative input values. They can also change the values of the most important parameters (price elasticity of demand, discount rate, etc.) directly on the GUI (Figure A. 6).

Afterwards, the users can execute the model and the model outputs for all the 44 districts in Baden-Württemberg are visualized in graphs (Figure A. 7) and maps (Figure A. 8), over the simulation time. Users can inspect the evolution of impact at different years or districts. These functionalities ensure the decision support tool to be efficient, assuming that the decisional contexts are appropriate.

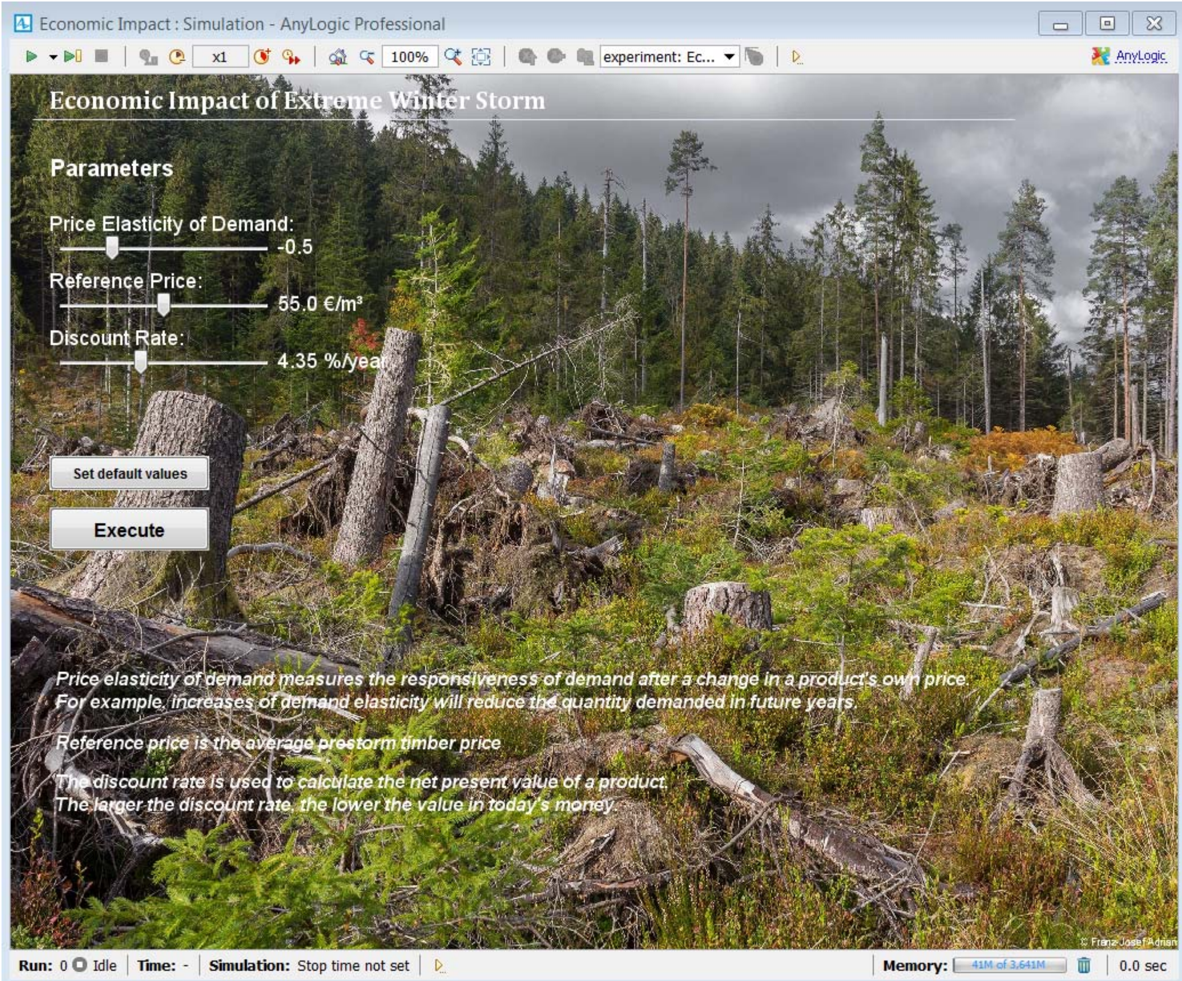

Figure A. 6: Overview of the graphical user interface of the decision support tool

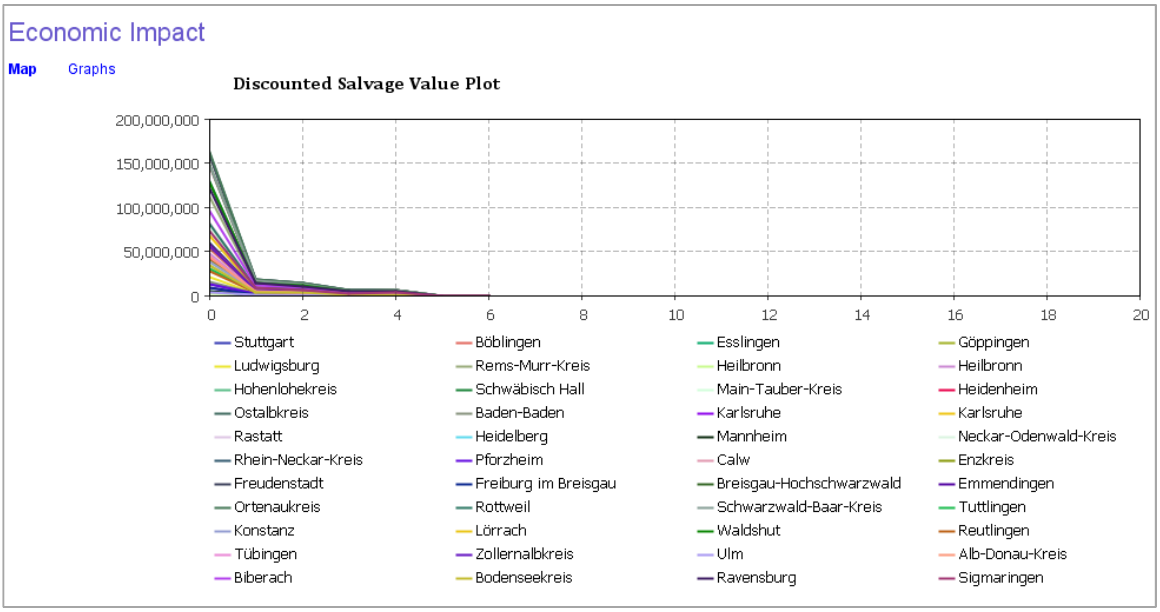

Figure A. 7: Simulation results of a management scenario (on graphs) within the decision support tool

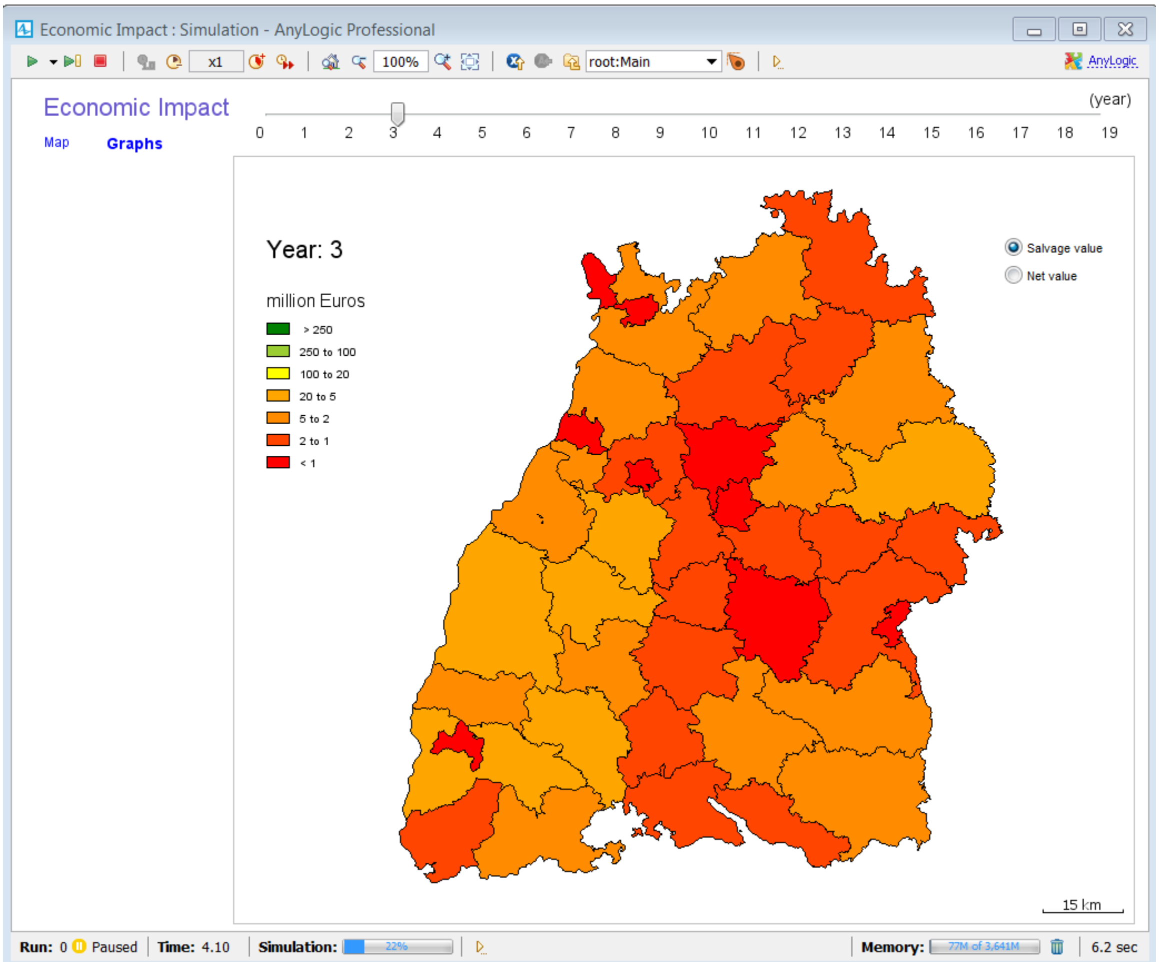

Figure A. 8: Simulation results of a management scenario (on maps) within the decision support tool