A System dynamics approach to assess economic impacts of extreme winter storms in forestry

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ABSTRACT: In forest management practices, assessment of dynamic impacts of extreme storms before the events occur would help in many ways, e.g., to assign marketing strategies or to optimise risk management plans, etc. This paper investigates the economic impacts of a stochastic extreme winter storm on the forest resources in Baden-Württemberg, Germany. Therefore, a system dynamics modelling approach coupled with Geographic Information System (GIS) is developed by considering theories of forest economics and simulating forest management related practices. The forestry sector is divided into five submodels to run the reference simulation in all the 44 districts in Baden-Württemberg. The economic impacts can thus be calculated and compared - at different simulation years or by discounting back the future values at present time for each district. The overall modelling approach and the results can help public and private forest owners to understand what the possible impacts would be, especially regarding the decisions on salvage operation and forest management.

KEYWORDS: System dynamics, forest resources, impact assessment, extreme winter storms, Baden-Württemberg

1. Introduction

Within a changing climate, hydro-meteorological natural hazards such as extreme winter storms 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 central Europe, the recent 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 in December 1999 in Europe, caused 19.2 billion US$ of damage to power grids and forest resources. Windstorm Klaus in January 2009, was responsible for around 40 million of m³ of timber damage in the south-western part of France (Nicolas, 2009). Other winter storms, e.g., Wiebke and Vivian in 1990 also caused significant forest damage.

The state of Baden-Württemberg is frequently hit by most of the above extreme winter storms. Several extreme winter storm hazard modelling and risk analysis was performed in Germany (Donat, Pardowitz, Leckebusch, Ulbrich, & Burghoff, 2011), (Heneka, Hofherr, Ruck, & Kottmeier, 2006), (Hofherr & Kunz, 2010). They identified Baden-Württemberg, especially the south-eastern parts of this state is most hazardous.

Extreme winter storms affect the forest resources and ecosystems - damage trees and ecosystems and thus cause significant economic losses. Economically significant events typically occur with low probabilities in locations that are not well known in advance

(Holmes, Prestemon, & Abt, 2008). Therefore, an analysis of economic impacts due to such events 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. It also helps to analyse optimal salvage/windthrow management alternatives and to plan 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.

An interdisciplinary research - focusing on Geographic Information Systems (GIS), forest economics and management practices, as well as system dynamics modelling approach - has been applied to analyse the impacts of a stochastic extreme winter storms on the forests in the state of Baden-Württemberg. This study aims to

- illustrate the dynamic interactions related to forest economy and management and to explain how impacts of extreme winter storms on forests evolve
- develop a system dynamics simulation model by incorporating, among other parameters, space and time.

Section 1 explains the problems and motivation of the research. The system dynamics modelling approach is formulated in Section 2. The results of the simulation run and a comparative discussion of different submodels are carried out in Section 3 and section 4, respectively. Finally, Section 5 summarizes the results and provides further insights into some open research questions.

2. Methodological approach

2.1 Model formulation

The proposed system dynamics modelling approach 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, etc. Therefore, based on the theoretical literature and forest management practices in Baden-Württemberg, the forestry sector is divided into five submodels (Figure 1): Salvage price submodel, Salvage value submodel, Standing timber value submodel, Forest clearing area value submodel and Pre-storm timber value submodel.

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 values before the extreme storm occurs. It is considered as reference value.

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 forest management best practices observed in the state of Baden-Württemberg.

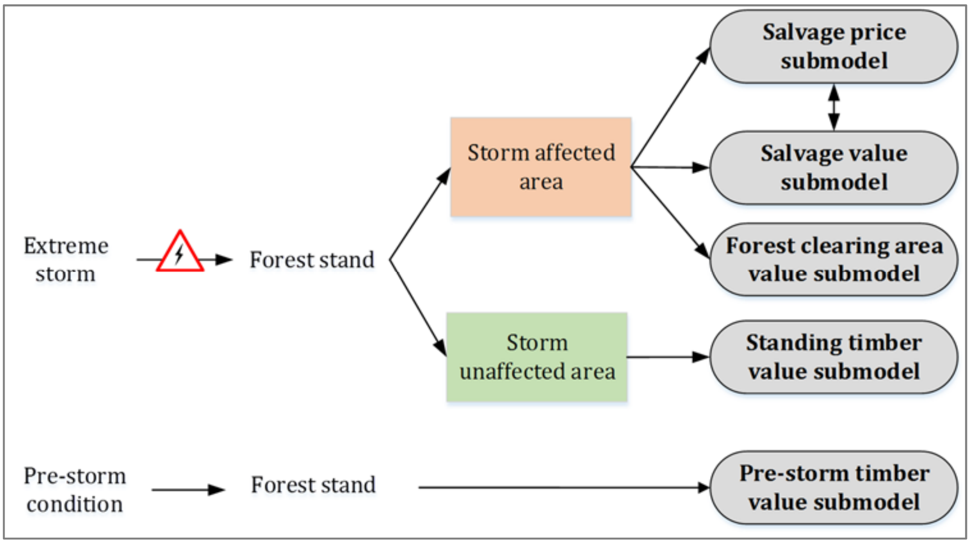

Figure 1: Description of the five submodels in system dynamics modelling approach

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 extents of these submodels vary as well. For instance, 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 (Table 1).

Table 1: Spatial and temporal characteristics of the five submodels

Condition	Submodels	Spatial resolution	Temporal extent, resolution/time steps
After storm	Salvage value	District	0 – 5 years, yearly
	Salvage price	Baden-Württemberg	0 – 5 years, yearly
	Forest clearing area value	District	0 – 20 years, yearly
	Standing timber value	District	0 – 20 years, yearly
Pre-storm	Pre-storm timber value	District	0 – 20 years, yearly

Afterwards, following the System dynamics modelling paradigm, boundary chart, subsystem diagram and causal loop diagrams are prepared. For example, Figure 2 illustrates some of the most important causal loops and the dynamic hypothesis of the model.

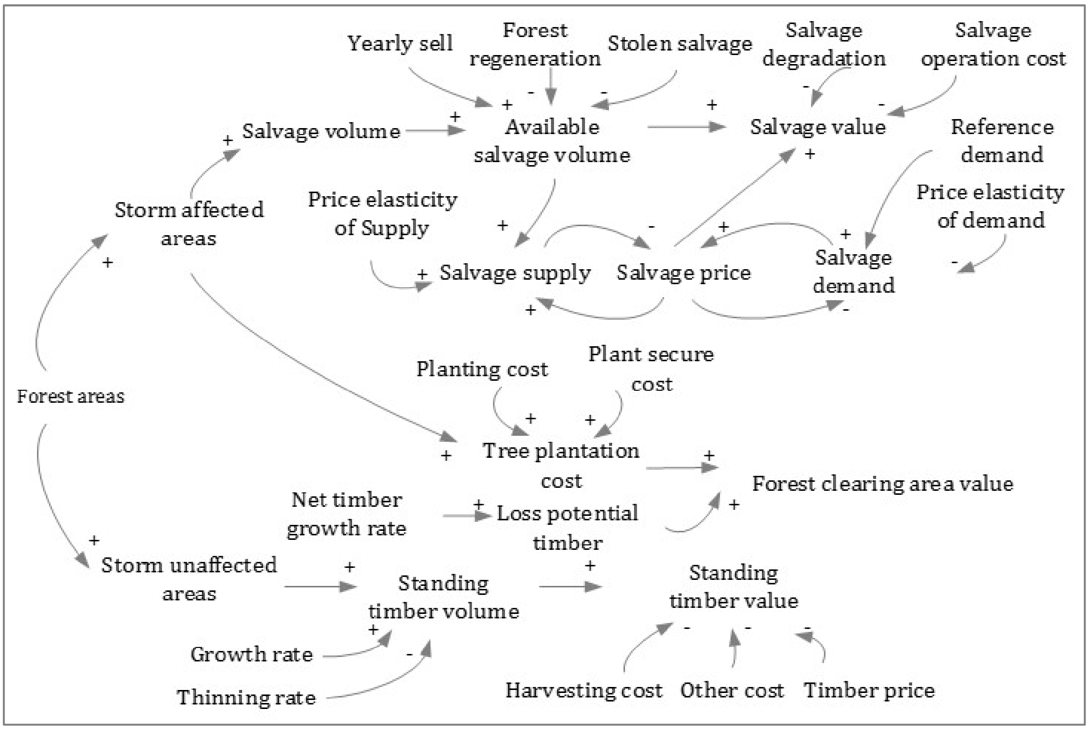

Figure 2: Causal loop diagram of the system dynamics model

2.2 Stock and flow diagrams of submodels

This generic price setting formulation proposed by (Sterman, 2000) has been adapted in this research to analyse and explain the salvage price submodel. The initial salvage price and reference price are given as input in the price formulation submodel. They are assumed to be the same as with the prestorm 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 simulation 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 are 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 the same for each model year. The reference supply – which is basically the available marketable timber after the winter storm - is calculated within the salvage value submodel by aggregating total volume of windthrow trees in all the districts in Baden-Württemberg.

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 3) 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 (1 – 7) describe the dynamic development of salvage price.

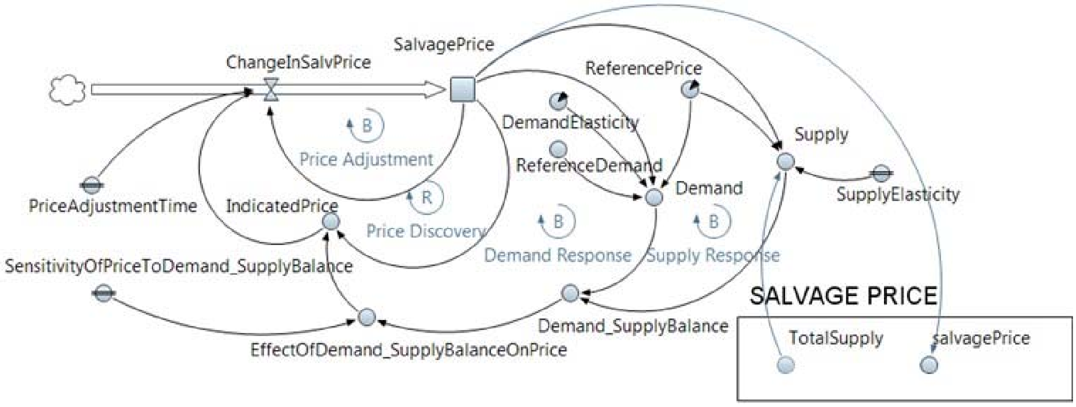

Figure 3: Stock and flow diagram of the salvage price submodel

The initial salvage price (Psl) adjusts to an indicated price (IPsl) over an integral given by the price adjustment time (PAT).

$$Psl\,[t+1] = Psl\,[t] + \int Pslch\,[t+1].dt \quad 1$$

$$Pslch\,[t+1] = (IPsl - Psl)/PAT \quad 2$$

Where, Pslch is the change in salvage price. The market clearing equilibrium price is unknown and therefore, the market makers form an indicated price (IPsl) based on the current reference price (Pref) and then adjusting it in response to the perceived balance (DS) between demand (Dsl) and supply (Ssl).

$$DS = Dsl / Ssl \quad 3$$

If demand of salvage (Dsl) exceeds supply (Ssl), the indicated price (IPsl) will rise and so will the actual salvage price (Psl). 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:

$$EDS = (Dsl / Ssl)^{sen} \quad 4$$

Where, $^{sen} > 0$ is the sensitivity of price to the demand supply balance. And the indicate price (IPsl) is then formulated as the salvage price (Psl) multiplied by EDS:

$$IPsl = Psl * EDS \quad 5$$

Earlier in the model, in order to find the market clearing salvage price (Psl), it is assumed that the demand and supply respond to price with constant elasticities. The demand (Dsl) and supply (Ssl) are determined endogenously considering the reference demand (Dref), reference supply (Vyasl) and their elasticities, as well as reference salvage price (Pref) and market clearing salvage price (Psl):

$$Dsl = Dref * (Psl / Pref)^{ed} \quad 6$$

$$Ssl = Vyasl * (Psl/Pref)^{es} \quad 7$$

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

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

The forest clearing area value submodel dynamically evaluates the costs associated with newly planted trees and potential loss of future timber value.

The standing timber value submodel calculates the total value of standing timber within the unaffected storm areas in each district. The standing timber value do not impose additional cost on the total economic impact of winter storms, rather it is calculated to evaluate the impact, by comparing it with other submodels, e.g., pre-storm timber value.

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 definition 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.

3. Reference simulation run

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 in all districts in Baden-Württemberg or in one or some particular highly vulnerable districts; throughout the simulation years or in a specific year. The reference simulation run is based on a set of assumptions, definitions and a literature review on different model parameters (Table 2).

Table 2: List of the model parameter and values for 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

The salvage price submodel is run for the whole state of Baden-Württemberg and 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, reference supply and demand, and the elasticities of supply and demand. The supply and reference supply of salvage are the same as 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 a separate study by (Murshed & Reed, 2016), theoretically about 176 million m³ 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 stolen salvage, about 138 million m³ 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 are 69, 28 and 28 million m³ and the model supply is 69, 14 and 12 million m³, 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 m³), salvage price and demand elasticity. In the first three years, the demand is approximately 7, 10 and 11 million m³, respectively (Figure 4, left).

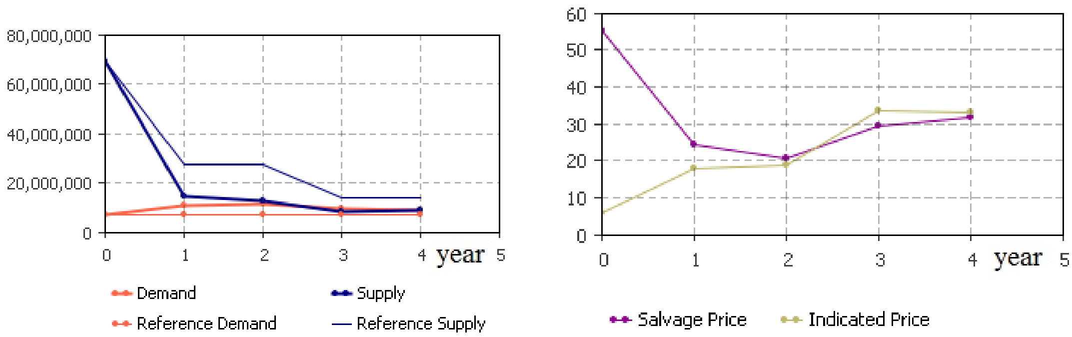

Figure 4: Determination of supply and demand of salvage (left), price setting process (right) of the salvage price submodel

Figure 4 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 model runs, is calculated based on the initial salvage price and the demand supply balance on price (Figure 4, 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/m³ but then the price grows again to 32 Euro/m³ in the fifth year.

Salvage value is calculated for all the 44 districts in Baden-Württemberg. For example, the district of Schwarzwald-Baar-Kreis generates around 7.4 million m³ of marketable salvage. The simulation demonstrates that in the first three years, approximately 3.7, 1.5 and 1.5 million m³ of salvage were brought to the market having a value of 183, 29 and 24 million Euros. But the costs associated with salvage operation incur roughly 30, 11 and 11 million Euros (Figure 5). The net value gained from selling salvage over the first five years are 153, 18, 13, 6 and 7 million Euros, which after considering a constant discount rate of 4.35% per annum, yields to 147, 17, 13, 5 and 6 million Euros at present values.

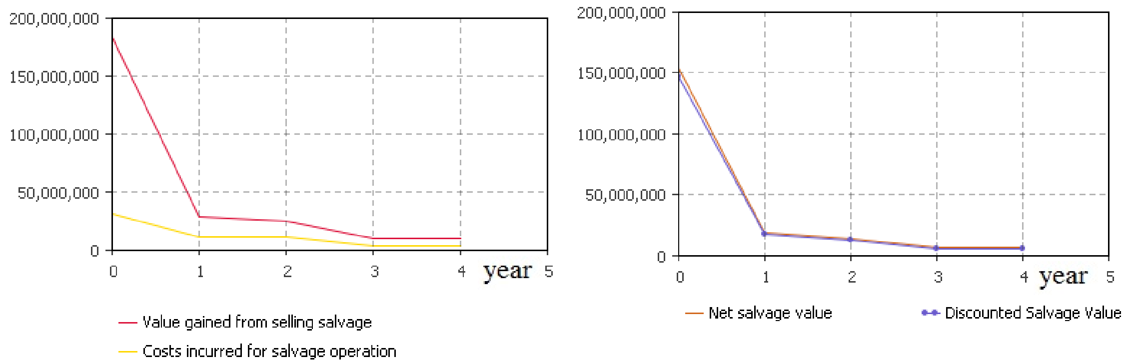

Figure 5: Salvage value gained and costs of salvage operation (left), net salvage value and discounted salvage value (right) in the district of Schwarzwald-Baar-Kreis

The discounted salvage value in all the districts in Baden-Württemberg is shown in Figure 6. Due to the degradation of salvage quality and less marketable salvage, the net values reduced dramatically after the second year. The districts of Ortenaukreis, Freudenstadt and Schwarzwald-Baar-Kreis experience maximum net monetary gains from the selling of salvage. The total net discounted salvage values in these districts are 206, 201 and 187 million Euros, respectively.

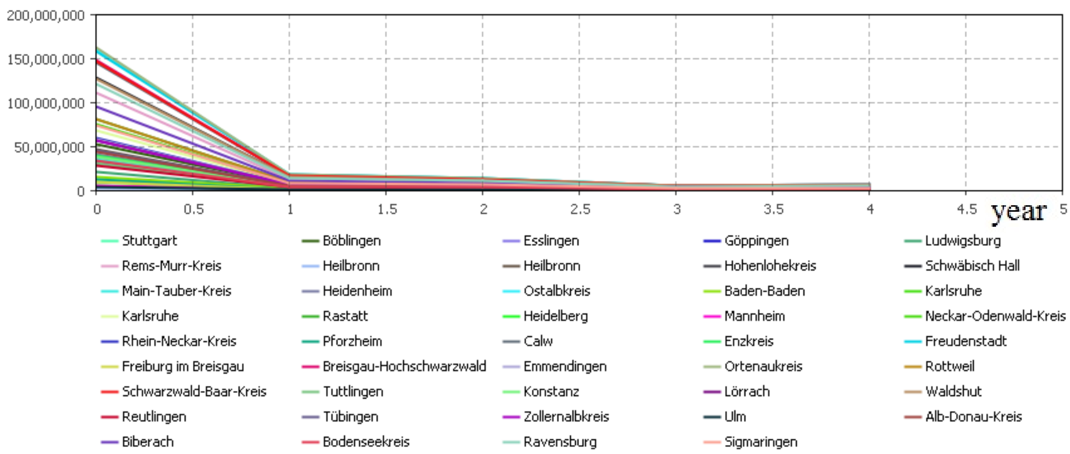

Figure 6: Discounted net salvage value in all the districts in Baden-Württemberg

Similarly, total costs associated with forest clearing area, values of standing timber and pre-storm timber are calculated for all the districts.

4. Discussion of results

The outcomes of reference simulation run 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. 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 capital gains (by selling salvage from storm affected areas), and the forest clearing area value submodel identifies the capital loss 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. Figure 7 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.

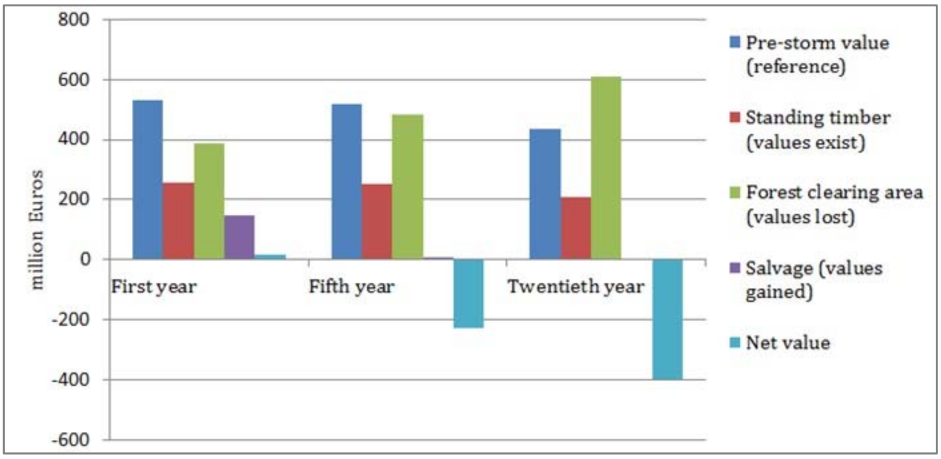

Figure 7: Comparison of discounted values of reference simulation runs of different submodels in the district Schwarzwald-Baar-Kreis

At first year, against a total pre-storm timber value of around 531 million Euros, the stochastic storm would generate approximately 147 million Euros net capital gain from the selling of salvage, 385 million Euros loss due to forest clearing areas and 255 million Euros capital stock as standing timber. The net value gained from such an event at first year is roughly 17 million Euros. In the fifth year, no marketable salvage is available and the cost overpasses the capital gains, 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 capital gains, 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 the first years, which leads to a negative net value of 400 million Euros.

The net value gained or lost is significantly different among 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 experiences net gain from selling of salvage over the first year. The districts, e.g., Ortenaukreis, Reutlingen, Alb-Donau-Kreis and Main-Tauber Kreis would gain a net value of over 300 million Euros each by selling of salvage (Figure 8). Over the fifth and twentieth simulation year, the net value gained reduced significantly among the districts. The districts of Schwarzwald kreis, Freudenstadt, Rems-Murr-Kreis, etc. continue to experience significant losses due to the extreme winter storm.

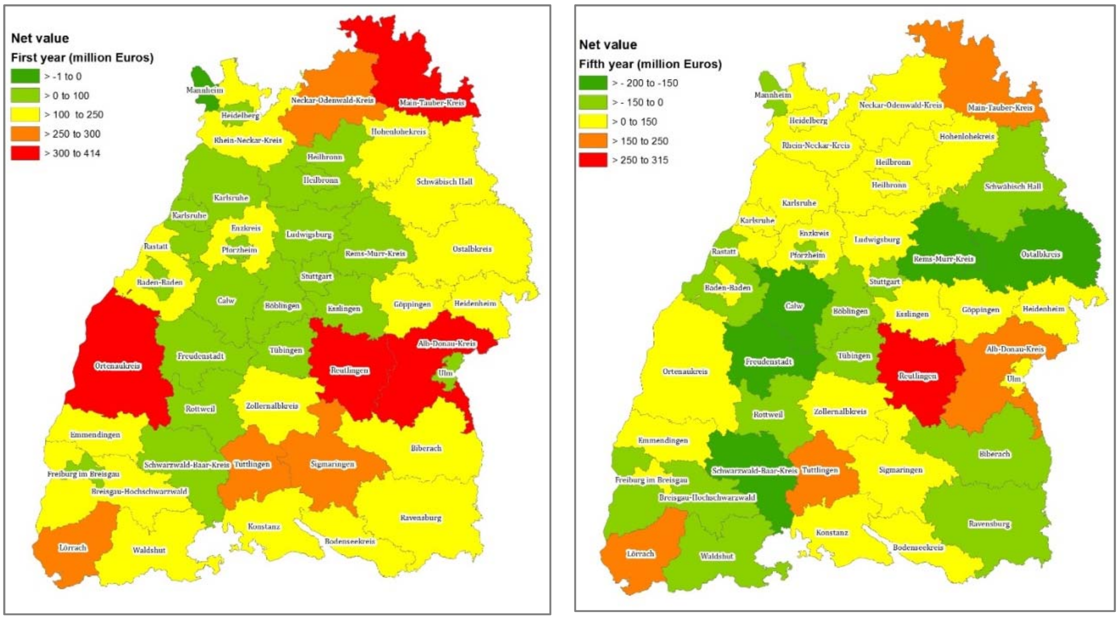

Figure 8: Spatial distribution of discounted net value gained or lost at the first and fifth simulation year

5. Conclusion and outlook

By knowing the possible future impacts after an extreme winter storm, forest managers and private forest owners would be able to prepare marketing strategies in order to control the sale of salvage timber, prevent the depreciation of its value, overcome unintended economic loss or plan sustainable forest management. Knowledge of the net value (to be gained or lost) is critical, since the total costs incurred in forest clearing areas, salvage operation as well as the value of the wood, is tied up for a prolonged period of time, leading to a heavy economic loss in some districts. Therefore, proposed system dynamics approach - with its scalability in terms of time and space - provides a fundamental basis to evaluate the impacts in forestry. It can be applied to operational challenges and policy analysis, as well as the exploration of possible future scenarios. Therefore, a decision support tool can be developed in future.

The proposed model is comprised of 35 variables and is developed into a graphical and mathematical representation of interaction, governing the long term behaviour of the complex forest system immediately after an extreme storm occurs. The system dynamics model and the related data could be further investigated considering the contemporary evolution of the forestry sector, especially in the salvage market.

A set of structural and behavioural validation tests are carried out to justify the acceptance of the methods. Moreover, some 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. Finally, four sensitivity analyses are performed to identify the impact of some of the most important parameters in model outcomes or exogenous variables. The price elasticity of demand proved sensitive to final salvage price, as a small variation of elasticity leads to a larger change in final salvage price.

However, some limitations exist. The non-market losses are difficult to estimate and require comprehensive modelling techniques. Disaster losses are almost exclusively limited to impacts measured by market values. Loss of leisure, a sense of location, historical monuments/cultural assets ('iconic' assets), and government services could be assessed by contingent valuation techniques but such techniques have yet to be employed (Cochrane, 2004). Thus, future studies should focus on estimating the non-market economic impacts.

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 the research. Moreover, the price setting of coniferous and deciduous trees could be modelled separately, since the prices differ significantly. 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.

The accuracy of the estimation of impacts may not be the most important concern, since extreme events differ from conventional events. Each disaster is unique, and exactly the same hazard will never occur twice. Hence, the impact analysis of disasters 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'. However, future research should endeavour to improve the accuracy of the model results.

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