How vulnerable is the protective function of Austria's mountain forests under climate change? A qualitative vulnerability assessment for protective forests in three selected regions.

Master thesis

by

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to obtain the academic degree Diplomingenieur der Forstwirtschaft (Dipl.-Ing.)

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August 2009

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Abstract

During the last decades the increase in temperature in the European Alps was about twice as high as the global average. This pattern is recurrent in climate change scenarios for the 21st century. The expected climatic changes may affect mountain forests at a broad range including the provision of forest goods and services. Here the focus is on the protective function against natural hazards. A scheme for a regional vulnerability assessment is developed and demonstrated by means of three case studies from Austria. Based on existing assessment schemes the sensitivity of forest ecosystems and hazardous processes to climate changes was inferred from current state and expected response regarding exposure to climate change. Blending ecosystem and hazard sensitivity yields potential impacts on the protective functions against flooding, debris flow, landslide, rock fall and snow avalanches. Regional adaptive capacity was estimated from a set of indicators reflecting forest infrastructure, administrative and organizational aspects. Vulnerability in three categories resulted from the combination of potential impacts and adaptive capacity. The assessment is based on a literature review, readily available regional forest inventory data and expert knowledge. For the analysis of the case studies the A1B climate change scenario from REMO-UBA was used. In the assessment two time periods were distinguished (2021-2050, 2071-2100). The selected case studies showed different vulnerabilities with regard to temporal development as well as to the magnitude of potential impacts. The results of the literature review revealed knowledge gaps with respect to climate change effects on forest regeneration and biotic disturbances, hazardous processes and extreme climate events. The application of the vulnerability assessment scheme is demonstrated successfully. However, due to the encountered knowledge gaps the results are subject to uncertainty.

Keywords: Protective forests, natural hazards, climate change, vulnerability assessment

Kurzfassung

Der Temperaturanstieg während der letzten Jahrzehnte war in den Alpen etwa doppelt so groß wie im globalen Durchschnitt. Dieses Muster setzt sich auch in den Vorhersagen für das 21. Jahrhundert fort. Diese erwartete Klimaänderung wird die Bergwälder und die von ihnen zur Verfügung gestellten Waldfunktionen auf mannigfaltige Weise beeinflussen. Der Schwerpunkt dieser Arbeit liegt auf der Schutzfunktion gegenüber Naturgefahren. Ein Schema für eine regionale Vulnerabilitätsabschätzung wird entwickelt und anhand von drei österreichischen Fallbeispielen angewandt. Basierend auf bereits existierenden Abschätzungsschemata wird die Klimasensitivität der Waldökosysteme und der Naturgefahren über deren jetzigen Zustand und deren erwartete Reaktionen auf eine Klimaänderung hergeleitet. Durch Verschneiden der Ökosystem- und Naturgefahren-Klimasensitivität ergeben sich potentielle Auswirkungen auf die Schutzfunktionen gegen Hochwasser, Muren, Hangrutschungen, Steinschlag und Lawinen. Die regionale Anpassungsfähigkeit wird mit der Hilfe von Indikatoren bezüglich der Waldinfrastruktur und administrativen sowie organisatorischen Aspekten angesprochen. Die Vulnerabilität ergibt sich aus der Kombination von potentiellen Auswirkungen und der Anpassungsfähigkeit. Die Abschätzung basiert auf einer Literaturstudie, zur Verfügung stehenden Waldinventurdaten und Expertenwissen. Für die Anwendung wird das Klimawandelszenario A1B verwendet und zwei Zeiträume (2021-2050, 2071-2100) werden betrachtet. Die Fallstudien zeigen unterschiedliche Vulnerabilitäten sowohl in zeitlicher Entwicklung wie auch bezüglich der Ausprägung der potentiellen Auswirkungen. Die Ergebnisse der Literaturstudie deuten auf Wissenslücken im Hinblick auf Effekte des Klimawandels auf Verjüngung, biotische Störungen, Naturgefahren und klimatische Extremereignisse hin. Die Anwendung des Schemas wird erfolgreich demonstriert, jedoch sind die Ergebnisse aufgrund der Lücken im jetzigen Wissenstand mit Unsicherheiten behaftet.

Schlagworte: Bergwald, Schutzfunktion, Naturgefahren, Klimaänderung, Vulnerabilitätsanalyse

Acknowledgements

I am grateful to Ao.Univ.Prof. DI Dr. Manfred J. Lexer for his valuable remarks, the discussions and his support. I also would like to thank DI Dr. Rupert Seidl for his helpful comments and encouragement. Furthermore thanks to DI Max Pöllinger, DI Michael Schiffer and DI Christian Weber of the Austrian Federal Service for Torrent and Avalanche Control (WLV) for providing information about their management districts and the discussion during the interviews.

I am deeply grateful to my parents and Ernestine Primus for their support and for making all this possible. I would like to dedicate this thesis to them. Special thanks go to Kathrin Motz for her patience, her encouragement and for sharing her life with me. With deep appreciation I want to thank Georg Hofbauer for the practice I could gain, the lessons I was allowed to learn in the forest and his friendship.

I would also like to thank my friends, in particular Gottfried Diwold, Andreas Drexel, Anna Maierhofer, Stefan Schörghuber and Gregor Unger, for the nice time and the distraction during our studies.

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1 Introduction

1.1 Problem statement

Forests are playing a major role in alpine environments. A multitude of goods and services is provided by forest ecosystems like timber, non wood forest products, biodiversity, clear drinking water and protection to mention but a few. In densely populated mountainous regions like, for instance, in Austria the protection against natural hazards is of high importance. The protection against natural hazards is also a vital factor when thinking about tourism, a major source of income in the European Alps and other mountainous areas around the world, as it is also sheltering tourism infrastructure and recreation areas.

Currently observed climate change is affecting the European Alps at twofold magnitude compared to the global average in terms of mean temperature increase (Christensen *et al.*, 2007). Both the observed and the projected climatic changes will strongly alter alpine ecosystems as well as communities depending on forest goods and services. Increasing temperatures and changing precipitation patterns will affect forest ecosystems as well as the occurrence of natural hazards. Therefore the investigation of climate related sensitivities, impacts, resulting vulnerabilities and possible adaptation options to mitigate negative impacts and utilize eventual benefits is of paramount importance. Whereas for timber production and also carbon sequestration plenty of literature is available (see Lindner *et al.*, 2008) currently there is very limited knowledge available with regard to climate change impacts on the protective function against natural hazards. Especially regionally explicit vulnerability assessments are needed as a crucial prerequisite to successful climate change adaptation in forest and natural hazard management. This is also stressed by the IPCC (e.g. Schneider *et al.*, 2007) by underlining the importance of regional vulnerability assessments in the Fourth Assessment Report.

1.2 Research objectives

The overall aim of this thesis is to develop a scheme for regional vulnerability assessments focusing on the protective functions of forests.

Specific objectives are:

(i) to review the current literature and provide a synthesis of the current scientific knowledge on climate change related effects on protective forests and natural hazards as knowledge base for the assessment,

(ii) to develop the assessment scheme,

(iii) to demonstrate the applicability of the assessment scheme by means of three case studies, and

(iv) to provide an overview on potential adaptation measures and strategies.

2 Methods

2.1 Definition of terms

The terms exposure, sensitivity, impact, adaptive capacity and vulnerability are used according to the IPCC third assessment report (IPCC, 2001). In the following the terms and their interrelationships will be introduced.

Exposure

Exposure is the nature and the degree to which a system is exposed to climate change containing mean climate characteristics, climate variability and frequency and magnitude of climatic extremes.

Sensitivity

Sensitivity is the degree to which a system is affected (adversely or beneficially) by climate change exposure. The climate change induced effects might be direct like increasing tree growth due to higher temperatures in mountain forests or indirect like increased tree mortality due to changing abundance of pests.

Potential impact

The potential impacts are a function of sensitivities. It subsumes all climate change induced impacts on an ecosystem function (e.g. timber production or like in this case protection against natural hazards) without consideration of human intervention.

Adaptive capacity

Adaptive capacity is the ability of a socio-ecological system to adjust to climate change including climate variability and extremes. Furthermore it enables the system to moderate potential damages, utilize opportunities or to cope with the consequences via planned anticipatory or reactive adaptation. There is spontaneous and planned adaptation.

Vulnerability

Vulnerability is defined as the degree to which a system (i.e. an ecosystem function) is susceptible, or unable to cope with, adverse effects of climate change, again including variability and extremes. Vulnerability is a function of potential impact and adaptive capacity.

Adaptation

The term adaptation refers to human interventions in the system, aiming at counteracting negative climate change impacts or taking opportunity of positive impacts in an anticipatory or reactive way (according to IPCC, 2001).

2.2 Literature review

The knowledge base for the vulnerability assessment is generated by a literature review. In this desk research scientific journals and available scientific project reports are screened focusing on forests and natural hazards with regard to climate change sensitivities, impacts and adaptation. Furthermore literature is scrutinized with regard to adaptive capacity and vulnerability concepts. A screening scheme based on a Microsoft Excel spread sheet has been developed to organize the information. The reviewed material is concentrating on the European Alps. Inner-alpine valleys and basins as well as the foothills of the Alps are as well within the scope of the literature review.

The natural hazards and respective protective functions of forest ecosystems regarded in the literature review as well as in the vulnerability assessment are a selection of the most important natural hazards occurring in the Alps. These hazards are:

(i) flooding,
(ii) debris flow,
(iii) landslide,
(iv) rock fall, and
(v) snow avalanche.

Natural hazards which can not be significantly influenced by protective forests have been disregarded. Such hazards are earthquakes, rock slides and in general hazardous processes whose magnitude (i.e. energy) is beyond the dissipative capacity of forests. Furthermore hazardous processes occurring in the glacial and periglacial regions have been disregarded because of the fact that this study is focusing on the protective function of forests which are spatially disjunct of the latter regions.

2.3 System analysis

The link between the literature review and the vulnerability assessment is the identification of dependencies within the analyzed system. The flowchart in figure 1 displays the interrelationships between climate change, forest, natural hazards and the protective function of forests. Climate change exposure and vulnerability are defined as starting-point and end-point respectively. Other forest services are not considered in this study.

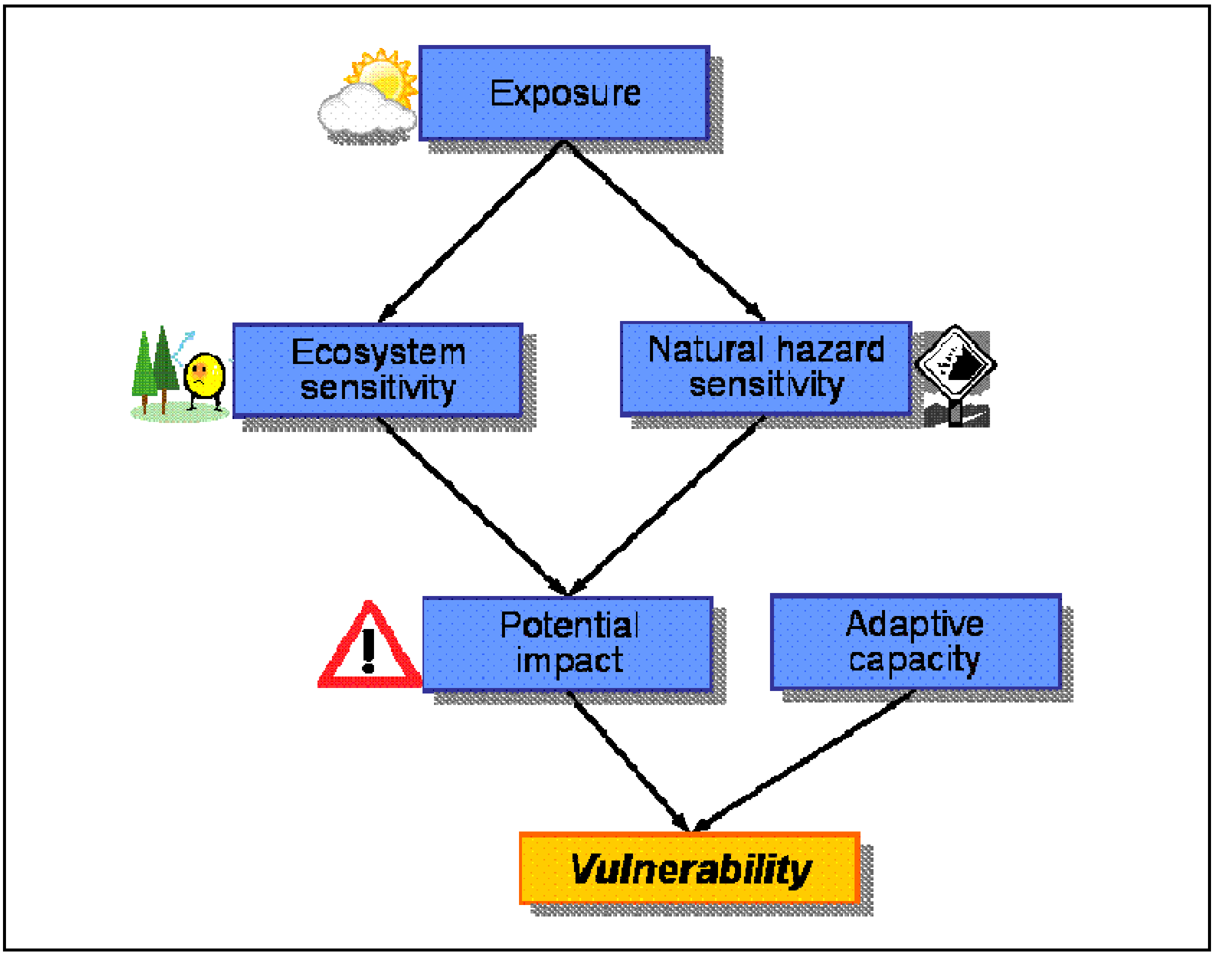


Figure 1: Structure of the vulnerability assessment and dependencies between the single elements.

2.4 Vulnerability assessment

The vulnerability assessment is based on two types of information sources, the results of the literature review concerning sensitivities and potential impacts and on regional data like climate projections (i.e. exposure) as well as characteristics of the test case areas.

The following assumptions are made according to the ATEAM vulnerability concept (e.g. Schröter *et al.*, 2004; Metzger *et al.,* 2008) which is modified to fit the needs of a vulnerability assessment focusing on protection against natural hazards.

The vulnerability (V) is assessed for a certain ecosystem service (es), in a certain region (x), under a specific climate change exposure (ex) and at a certain point in time (t). It is a function of potential impacts (PI) and adaptive capacity (AC) (cf. equation 1). The potential impacts are defined as a function of forest (S_f) and natural hazard sensitivities (S_{nh}) (cf. equation 2). Extending the ATEAM vulnerability concept in the current approach the sensitivity is seen as a function of the current state of the system (St_f and St_{nh}) and the expected system response to climate change (R_f and R_{nh}) (cf. equation 3 and 4). Luers (2005), for example, introduced an approach using exposure, sensitivity and state to derive vulnerability. Lexer and Seidl (2009; see also Seidl *et al.,* submitted for publication) use a similar approach which is implemented in a modified form in the assessment of sensitivities in this study.

$$V\ (es, x, ex, t) = f\ (PI\ (es, x, ex, t), AC\ (es, x, ex, t)) \qquad \text{(eq. 1)}$$

$$PI\ (es, x, ex, t) = f\ (S_f\ (es, x, ex, t)\ , S_{nh}\ (es, x, ex, t)) \qquad \text{(eq. 2)}$$

$$S_f\ (es, x, ex, t) = f\ (St_f\ (es, x, ex, t), R_f\ (es, x, ex, t)) \qquad \text{(eq. 3)}$$

$$S_{nh}\ (es, x, ex, t) = f\ (St_{nh}\ (es, x, ex, t), R_{nh}\ (es, x, ex, t)) \qquad \text{(eq. 4)}$$

In this case the ecosystem service (es) addressed will be the protective function against a certain natural hazard (flooding, debris flow, landslide, rock fall and avalanche). The region (x) for which the assessment is done will be defined by the case study. The projections of a regional climate model will be used to represent regional exposure (ex) and the assessment will be conducted for two time steps (t)

(2021 – 2050 and 2071 – 2100). In the following the methodology for the different assessment steps will be presented chronologically according to figure 2.

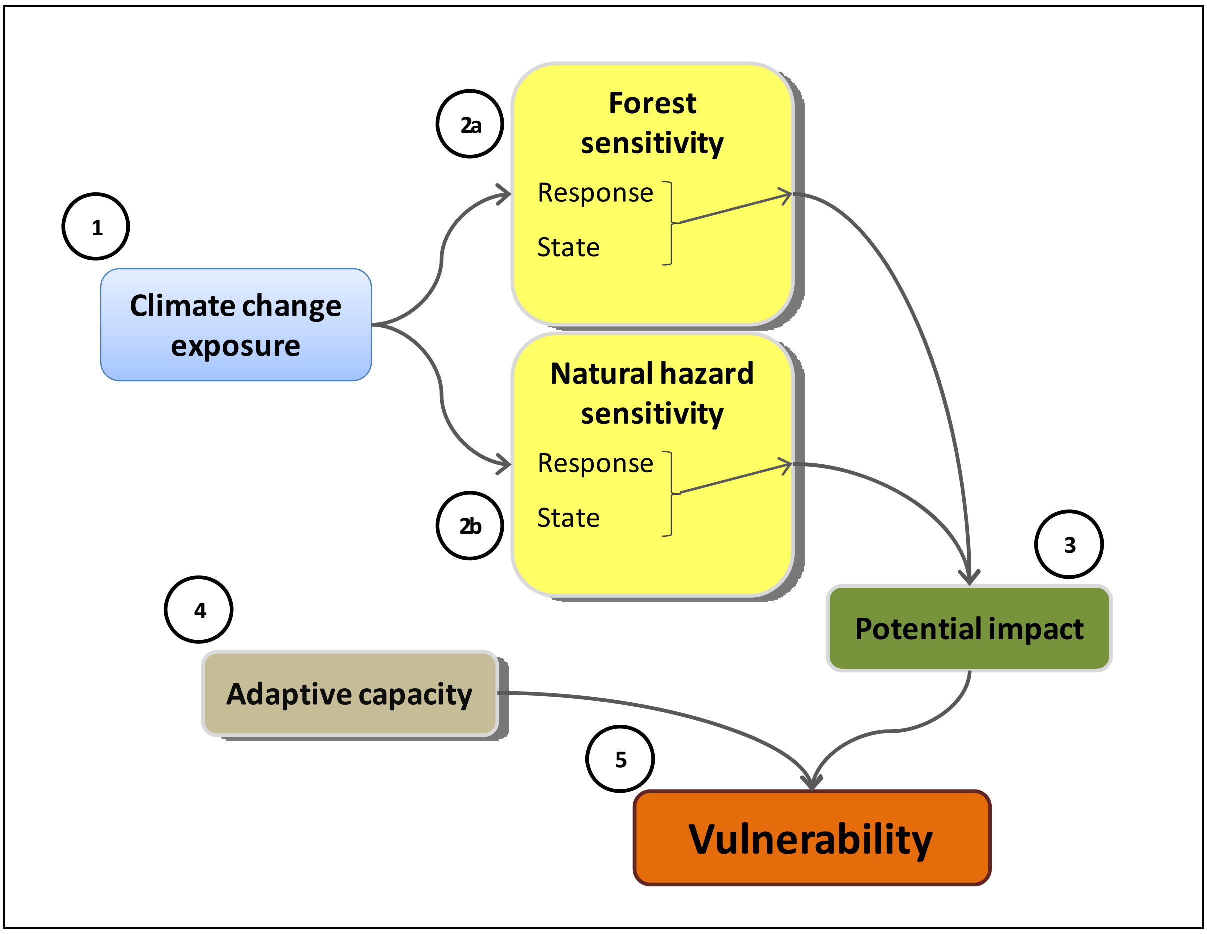


Figure 2: Flowchart showing the assessment steps of the vulnerability assessment and the causal interrelationships.

2.4.1 Exposure

The climate change exposure is derived from regional climate change projections available at Austrian Forest Inventory (AFI) plots. Three transient climate change scenarios at monthly resolution (temperature, precipitation, global radiation, vapor pressure deficit) are available for the AFI plots. The regarded scenarios are A1B, A2 and B1 (according to Nakicenovic *et al.*, 2000). For these emission scenarios output of ECHAM5 had been used to run projections until 2100 by the Max Planck Institute using the regional climate model REMO UBA. These data are available in a spatial resolution of 10 x 10 km resulting in 870 grid cells in Austria. To obtain climate projections at AFI plots the climate change signals of the regional climate model are averaged over the surrounding nine grid cells and imposed on a baseline climatology represented by the mean values of the climate parameters from the instrumental period 1961-1990. These baseline data were interpolated to the AFI plots from the network of weather stations of the Zentralanstalt für Meteorologie und Geodynamik (ZAMG) (Haas and Formayer, 2009; unpublished).

For the vulnerability assessment two time slices from 2021 – 2050 and from 2071 – 2100 in comparison with a climate baseline represented by the period from 1971 to 2000 will be used. From these time series data mean annual temperature and precipitation as well as mean values for summer (June, July and August) and winter season (December, January and February) are calculated for both time slices. With respect to climatic extreme events and their potential development evidence from the literature review will be taken into account for the assessments as they can not be derived from the data at hand.

2.4.2 Sensitivity

To evaluate the climate change sensitivity of forest ecosystems and natural hazards key indicators are introduced.

(i) Forest **growth** is defined as the annual increment of stem-wood per ha [$m^3*ha^{-1}*a^{-1}$].

(ii) Within the context of this study the indicator **mortality** includes abiotic (e.g. drought, winter desiccation, forest fire, wind throw, and other mechanical damages killing mostly young plants like e.g. snow gliding) and biotic (pests, diseases) reasons. The average share of damaged timber comprising of salvage from abiotic and biotic damages in the annual felling is taken as indicator for the assessment of the current state regarding mortality (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b). For the estimation of forest ecosystem responses to climate change abiotic and biotic mortality will be addressed separately.

(iii) **Regeneration** is defined as the ability of a tree species to regenerate naturally; anthropogenic influences such as for example overly large deer populations are not considered in the assessment.

(iv) The indicator **tree line** is defined as the altitudinal position of the actual tree line in comparison with the potential climatic tree line.

(v) The indicators used for the natural hazards are:

(vi) **Frequency**, which is defined as the occurrence interval of potentially harmful events.

(vii) **Magnitude** is represented by the mean damage. The mean damage is defined as the average damage caused by all potentially harmful events.

In the following, to provide clarity, the appraisal procedure for forest ecosystem and natural hazard sensitivities will be presented separately.

2.4.2.1 Forest ecosystem sensitivity

For each of the indicators used for the forest ecosystem the current state (St_f) and response to climatic changes (R_f) will be evaluated according to figure 3. As prerequisites information about the regional climate change exposure and current forest characteristics are needed besides the knowledge base generated by the literature review. The information about forest characteristics is obtained from the Austrian Forest Inventory (AFI) (Anonymous, 1997, 2002a) and the Holzeinschlagsmeldung (HEM), an annual federal / provincial felling documentation based on estimates (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

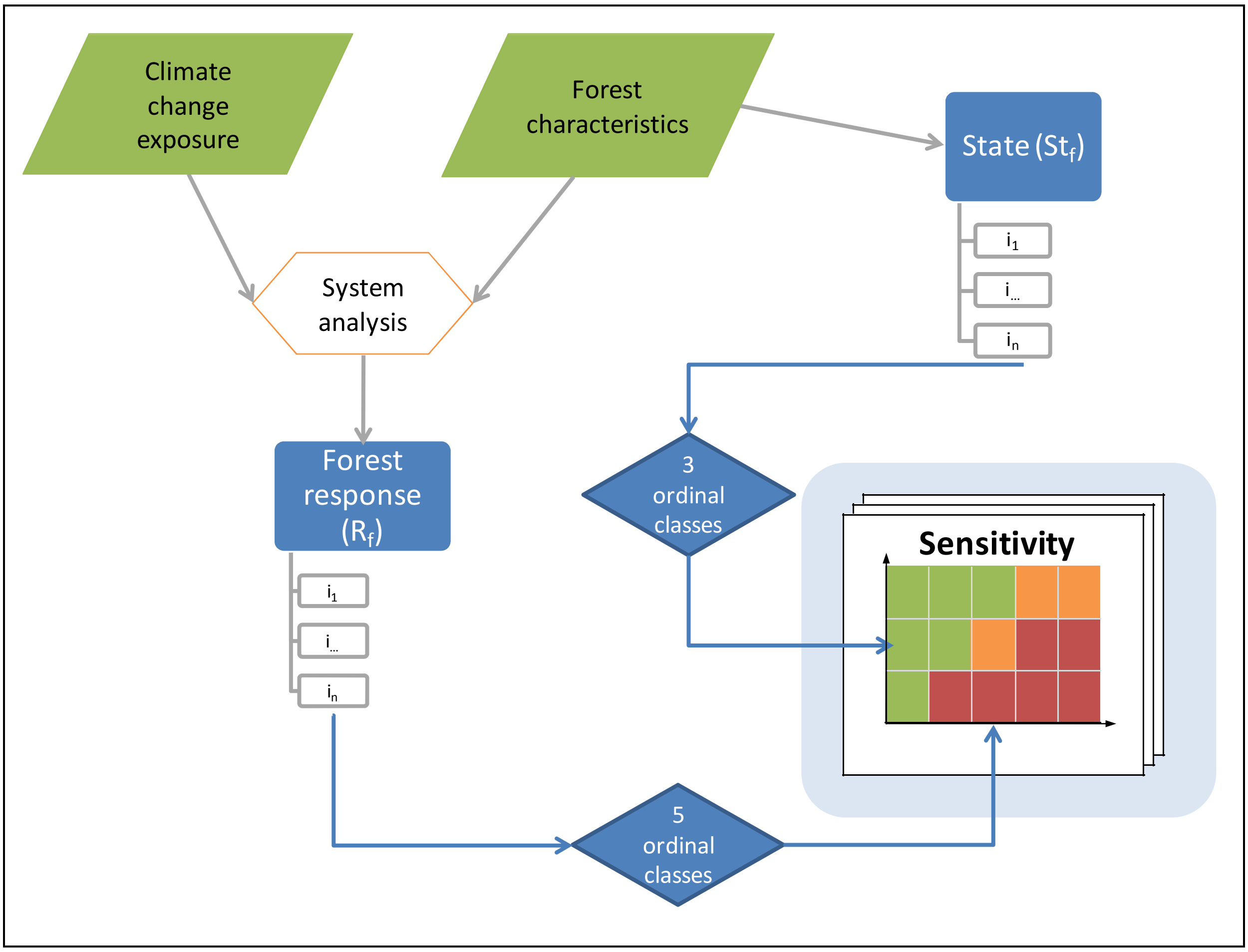


Figure 3: Graphical illustration of the assessment of forest sensitivity. The data input (green) consists of information concerning climate change exposure and regional forest characteristics. This information is processed in the systems analysis (red) and assessments (blue) for the forest response are made for each indicator. Combining discrete system states and responses per indicator generates the forest ecosystem sensitivity.

To estimate the current state and future responses of forests a multi-level stratification into tractable assessment units was applied. Tree species are the first level stratum, further split into altitudinal belts and stand development phases according to figure 4. For the indicators growth, regeneration and tree line a subdivision in development phases will not be applied and the indicator tree line will only be assessed for the altitudinal zone >1200m. The development phases are defined as follows: youth refers to youth and thicket stages (from saplings to a height of 10 m with a diameter at breast height (DBH) of roughly 10 cm), pole to pole stand stages (from 10 to 20 cm DBH), and timber to timber stage (>20 cm DBH) according to Mayer (1992). Age class information of the AFI was used to approximate the stand development phases according to table 1. For the evaluation of the responses of the indicators abiotic and biotic mortality development phases are considered as trees in different development phases show different susceptibilities to abiotic and biotic stress. To implement this approach the following information has to be derived from the AFI:

(i) Area share of altitudinal belts,
(ii) area share of the tree species in the altitudinal belts, and
(iii) the area share of the age classes in the altitudinal belts.

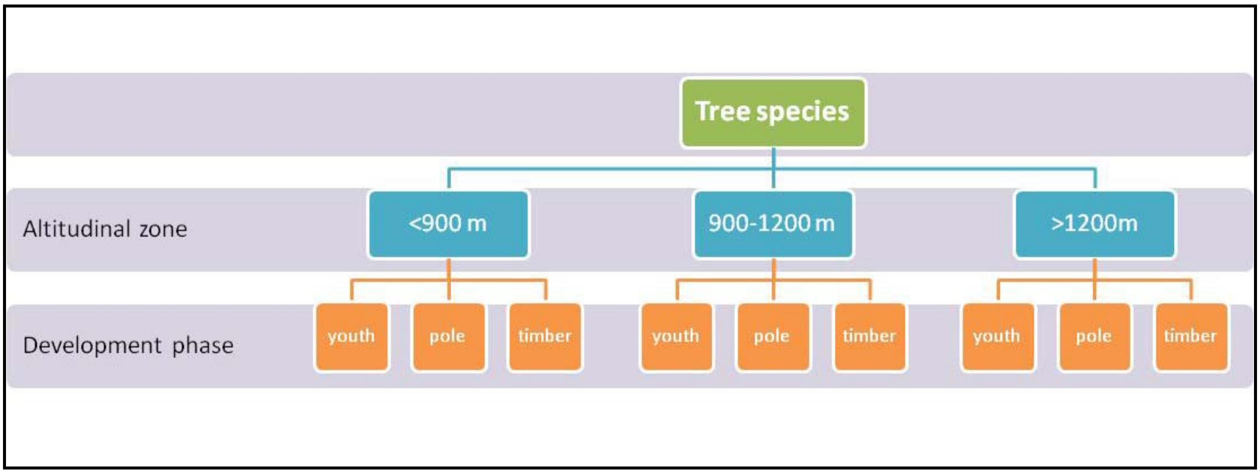


Figure 4: Stratification of the forests in the case study regions to appraise the current state and forest ecosystem response to climate change.

Table 1: Approximation of development phases in three altitudinal zones according to the age class information obtained by the AFI.

Development phase	< 900 m	900 – 1200 m	> 1200 m
Youth	0 to 20 years	0 to 20 years	0 to 20 years
Pole stage	21 to 40 years	21 to 40 years	21 to 60 years
Timber stage	> 40 years	> 40 years	> 60 years

As first step in the appraisal of the forest sensitivity in a case study region the current forest state is examined for each indicator at assessment unit level. The appraisal uses ordinal classes according to table 2.

Table 2: Evaluation classes (1 = good, 2 = average, 3 = poor) used to estimate the current state of the forest ecosystem indicators.

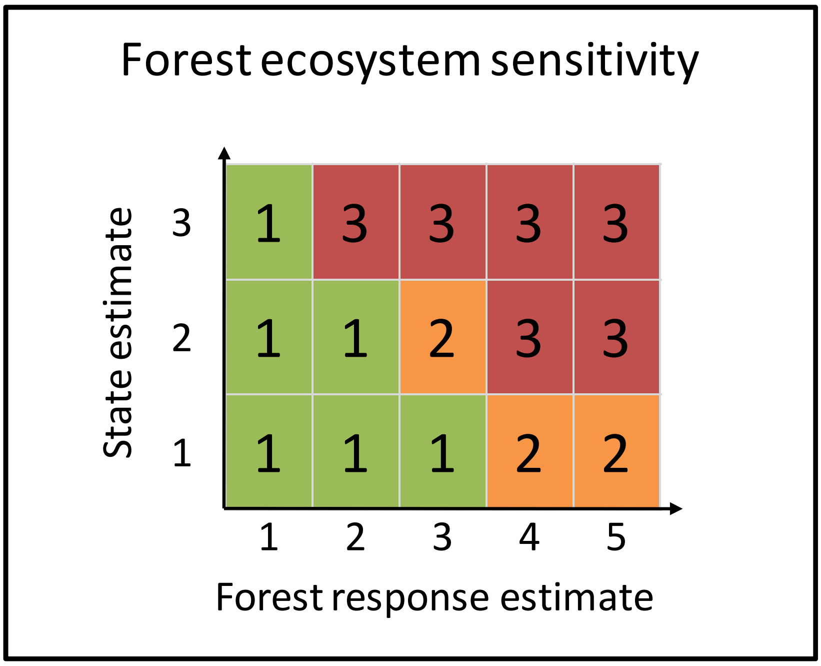
Class	Growth	Mortality	Regeneration	Tree line
1	Increment > 8 $m^3*ha^{-1}*a^{-1}$	< 20% share of damaged timber in the annual felling	The tree species is able to regenerate naturally in more than 90% of the sites.	The actual tree line corresponds well with the potential tree line.
2	Increment between 6 to 8 $m^3*ha^{-1}*a^{-1}$	Damaged timber share between 20 and 40%	Natural regeneration is possible on 60 to 90% of the sites	In some locations the actual is lower than the potential tree line due to land use practices.
3	Increment < 6 $m^3*ha^{-1}*a^{-1}$	Damaged timber share > 40%	Natural regeneration is only possible at less than 60% of the sites.	In the majority of locations the actual is lower than the potential tree line.

The next step is to estimate the response of the indicators under climate change exposure. The same stratification in altitudinal belts, tree species and stand development phases as for the forest state assessment is used. Table 3 displays the ordinal classes used to evaluate forest response to climate change.

Table 3: Definition of the five classes for estimating the response to climate change exposure of forest ecosystem indicators.

Class	Description
1	Positive response
2	Hardly any positive or negative response
3	Slight negative response
4	Moderate negative response
5	Strong negative response

Combining the assessments made for state and response yields a realistic and transparent estimate of forest sensitivity. The worse the current state the bigger is also the negative influence of potentially negative response estimates (cf. figure 5). Figure 5 presents the aggregation of state and response categories. The two ordinal assessment results are combined to fit a tripartite ordinal scale according to the matrix depicted in figure 5. According to the matrix sensitivity class 1 represents a negligible level of negative or even positive sensitivities, class 2 is characterized by slight to moderate negative sensitivities and class 3 is representing strong negative sensitivities.



State estimate \ Forest response estimate	1	2	3	4	5
3	1	3	3	3	3
2	1	1	2	3	3
1	1	1	1	2	2

Figure 5: The sensitivity matrix used to aggregate state and response estimates per indicator to forest ecosystem sensitivities (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

As these indicator-specific estimates are now available at assessment unit level they have to be aggregated to provide values at case study level for each indicator. Subsequently the indicator results need to be combined to yield an overall result for forest ecosystem sensitivity for a case study region. For this purpose the ordinal classification of forest ecosystem sensitivities is converted into a cardinal scale to allow for an additive aggregation procedure.

One simple standard approach is to replace ordinal classes by adhoc cardinal values (i.e. scoring). However, this either results in implausible even distances between classes or in intransparent scoring procedures. In the current study the Analytic Hierarchy Process (AHP; Saaty 1977) is used to compare the original ordinal sensitivity classes pairwise with regard to preferability on Saaty´s ratio scale (table 4).

Table 4: Saaty´s ratio-scale for pairwise comparisons (Saaty, 2001).

Rating	Linguistic term
9	**Extremely** more preferred
7	**Very strongly** more preferred
5	**Strongly** more preferred
3	**Moderately** more preferred
1	**Equally** preferred
1/3	**Moderately** less preferred
1/5	**Strongly** less preferred
1/7	**Very strongly** less preferred
1/9	**Extremely** less preferred
2,4,6,8 and 1/2,1/4, 1/6, 1/8 are intermediate values	

From the pairwise comparison matrix the eigenvector with the largest eigenvalue is calculated and used as preference for the related element (i.e. sensitivity class). Table 5 shows these preference values as well as their cumulative transformation.

Using the cumulative values the three sensitivity classes can be displayed on a cardinal scale between 0 and 1 (figure 6). The cardinal sensitivity values for each assessment unit (tree species, altitudinal belt, stand development phase) are additively aggregated by building weighted mean values according to the area share of the assessment units. This is resulting in indicator specific cardinal sensitivity estimates.

Table 5: AHP preference values obtained from pairwise comparisons of the sensitivity classes and resulting cardinal values for the sensitivity classes (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

Sensitivity class	AHP preference value	∑ preference values	AHP class values
1	0,633	0,633	0,316
2	0,260	0,894	0,763
3	0,106	1,000	0,946

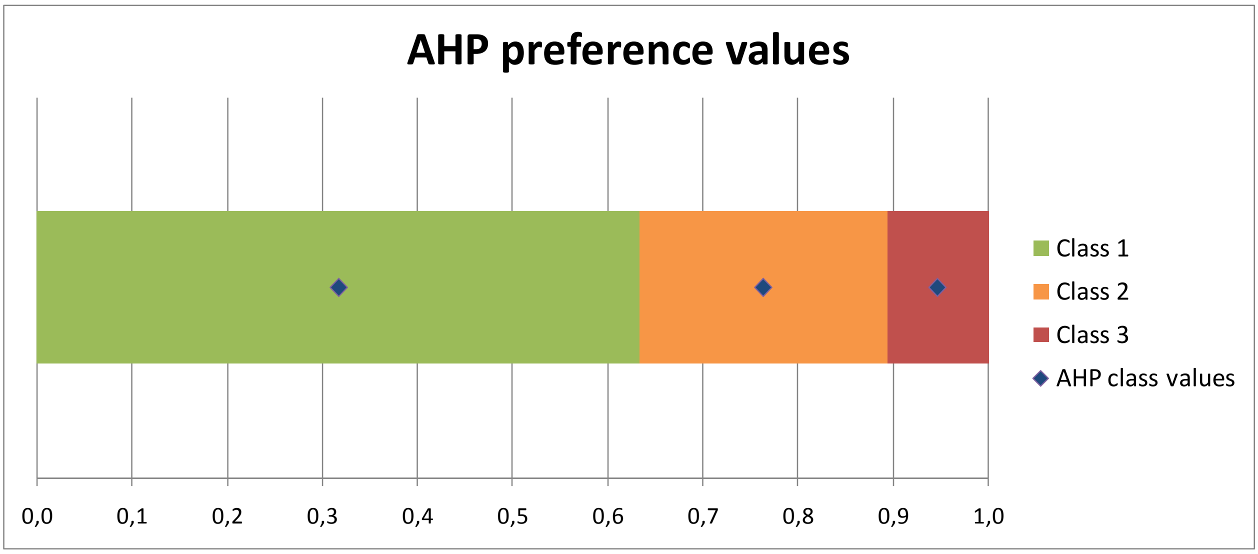


Figure 6: Graphical illustration of the sensitivity classes on a cardinal scale between 0 and 1 according to the cumulative sums of AHP preference values. The representative cardinal values for the ordinal sensitivity classes (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity) are indicated by the blue diamonds.

As different protective functions are *inter alia* defined by different stand characteristics also the sensitivities of regarded indicators are of different importance. Thus, for each protective function a specific forest ecosystem sensitivity value is calculated. The weights of the forest ecosystem indicators are determined from pairwise comparisons employing again the AHP approach.

The resulting preference values, as displayed in table 6, are used as weights in an additive aggregation procedure. This is resulting in cardinal forest sensitivity estimates for each protective function.

Table 6: AHP preference values used as weights for the forest ecosystem indicators.

Natural hazard	Indicator weights					
	Growth	Abiotic mortality	Biotic mortality	Regener-ation	Tree line	Sum
Flooding	0,06	0,45	0,30	0,14	0,05	1
Debris flow	0,03	0,43	0,33	0,12	0,09	1
Landslide	0,04	0,46	0,32	0,10	0,09	1
Rock fall	0,10	0,41	0,27	0,18	0,04	1
Avalanche	0,03	0,39	0,29	0,17	0,12	1

The resulting forest sensitivity values can be interpreted as such or discretized again to keep consistency with the original ordinal classes. Table 7 shows the cut-off values for the conversion of the cardinal sensitivity values into discrete classes.

Table 7: Cut-off values for the conversion of cardinal sensitivity values into discrete sensitivity classes (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

Sensitivity class	Threshold
1	Cardinal sensitivity value < 0,633
2	0,633≤ cardinal sensitivity value ≤ 0,894
3	Cardinal sensitivity value >0,894

After this procedure for each protective function an ordinal forest sensitivity value is available and ready to use for the appraisal of potential impacts.

2.4.2.2 Natural hazards

The procedure for the natural hazards is depicted in figure 7. According to the modus operandi for the forest ecosystem also for the appraisal of natural hazard sensitivities the current state of the indicators has to be estimated. Therefore the current frequencies and magnitudes of the regarded natural hazards have to be estimated according to table 8 and table 9. The required information is obtained through interviews with the regional staff of the Austrian Federal Service for Torrent and Avalanche Control in the case study regions. For this purpose an interview guideline was created to standardize the information obtained from these expert interviews (see Appendix D – Interview guideline). A further stratification of the assessment unit as it is done for the forest assessments is not applied.

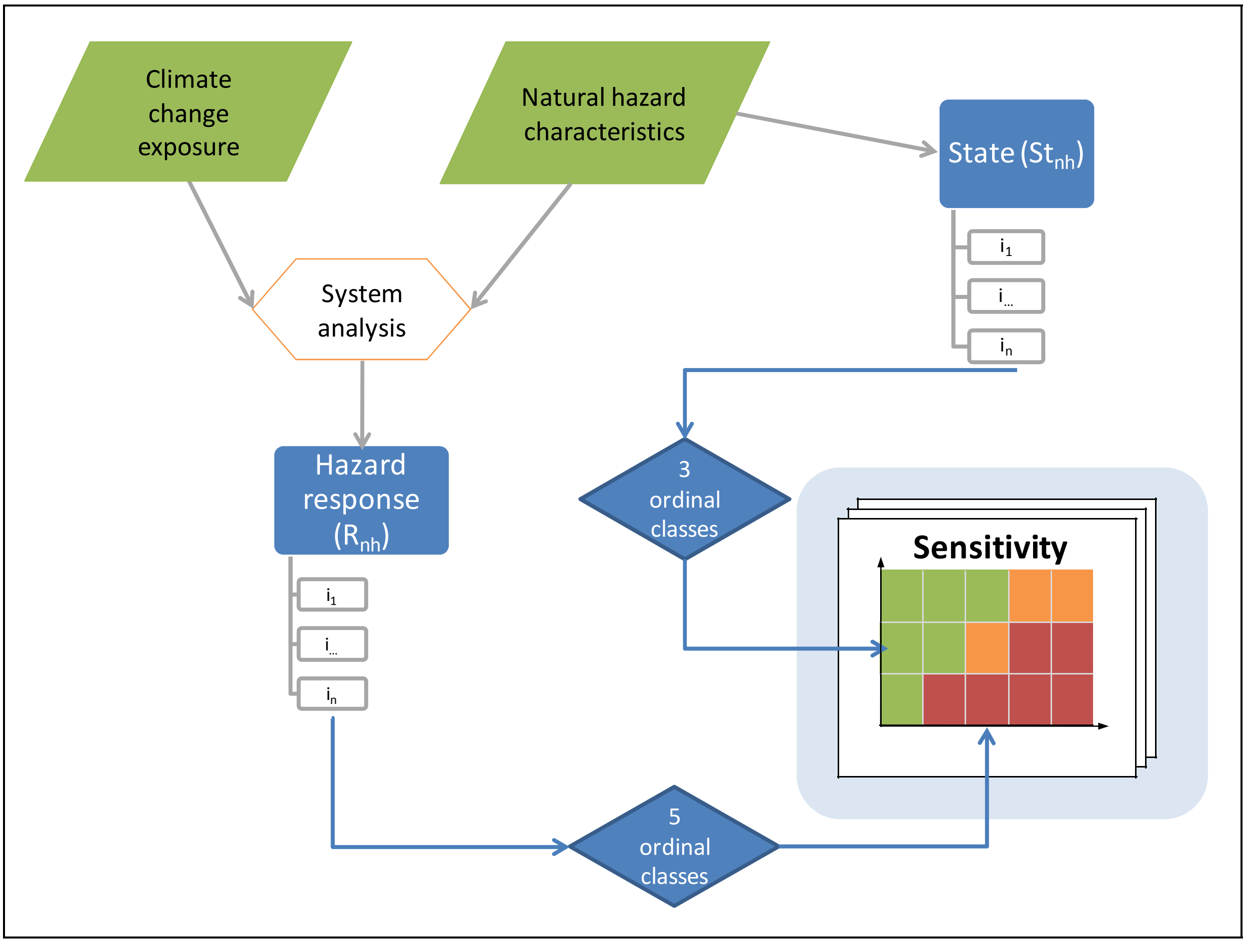


Figure 7: Graphical illustration of the appraisal procedure for natural hazards sensitivity. The data input (green) consists of information concerning climate change exposure and regional natural hazard characteristics. This information is processed according to the systems analysis (red) and assessments (blue) for the natural hazard response are made. The combination of the current state and the response to climate change exposure generates the natural hazard sensitivity.

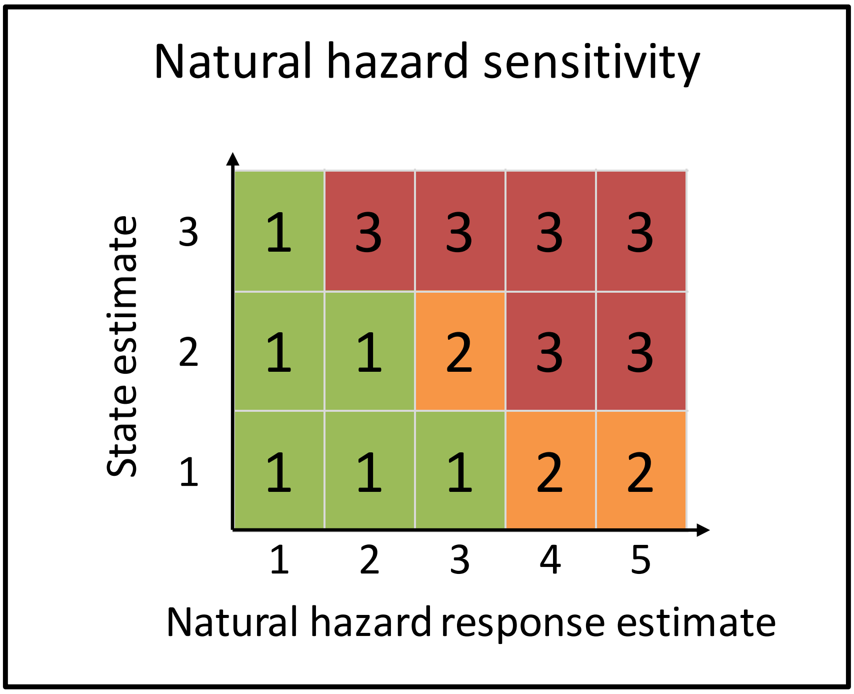
Table 8: Ordinal classes used to characterize the current frequency of natural hazards.

Class	Frequency	Description
1	Seldom	Potentially harmful events are happening less often than once per year within the region.
2	Frequent	Potentially harmful events are happening between 1 and 10 times per year within the region.
3	Very frequent	Potentially harmful events are happening more often than ten times per year within the region.

Table 9: Ordinal classes used to characterize the current magnitude of natural hazards.

Class	Magnitude	Description
1	Small	The average potentially harmful event is considered to be of small magnitude. E.g. little damages observed like punctual disruptions of traffic infrastructure.
2	Medium	The average potentially harmful event is considered to be of medium magnitude. E.g. medium damages observed such as disruptions of traffic infrastructure or damages and destruction of single buildings.
3	Large	The average potentially harmful event is considered to be of large magnitude. E.g. large damages observed such as destruction of traffic infrastructure and settlements.

Analogously to the forest assessments the next step is to estimate the climate change induced responses of the indicators. This is done without further stratification on basis of the literature review and expert knowledge of local managers and the author. Thereafter these response estimates are combined with the estimates for the hazard state to yield hazard sensitivity on an ordinal scale (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity) according to figure 8.



Natural hazard sensitivity

State estimate 3	1	3	3	3	3
2	1	1	2	3	3
1	1	1	1	2	2
	1	2	3	4	5

Natural hazard response estimate

Figure 8: The sensitivity matrix used to combine state and response estimates of hazard indicators to natural hazard sensitivities (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

As no further stratification of the assessment units has been conducted, in contrast to the assessments for the forest ecosystems, no aggregation is necessary at indicator level. However, to provide sensitivity values for each of the natural hazards the estimates for the hazard indicators have to be aggregated. This is done by using a matrix combining the assessment results for frequency and magnitude to three ordinal classes as depicted by figure 9. The resulting classes are negligible negative or even positive sensitivity (class1), slight to moderate negative sensitivity (class 2) and strong negative sensitivity (class3).

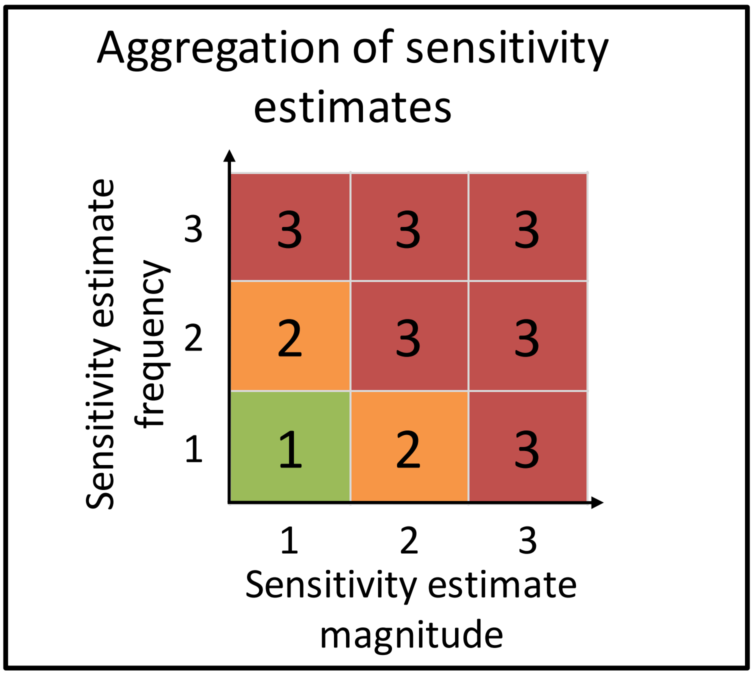


Figure 9: Aggregation of the sensitivity estimates for the indicators frequency and magnitude to obtain a hazard specific sensitivity (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

After this procedure for each hazardous process an ordinal natural hazard sensitivity value is available.

2.4.3 Potential impact

The next step following the assessment of (eco-) system sensitivities is the generation of the potential impacts. To assess the potential impact of climate change on a specific protective function the sensitivities of the forest ecosystem and of a natural hazard have to be combined. This is done by using a 3 x 3 matrix providing an output of again three classes of hardly any or small (1), medium (2) and strong (3) potential negative impacts on protection against a certain hazard (figure 10). The response is not symmetric as sensitivities in the natural hazard system are judged to be of stronger influence than sensitivities of the forest ecosystem. For each protective function a potential impact estimate on an ordinal scale is available at this stage.

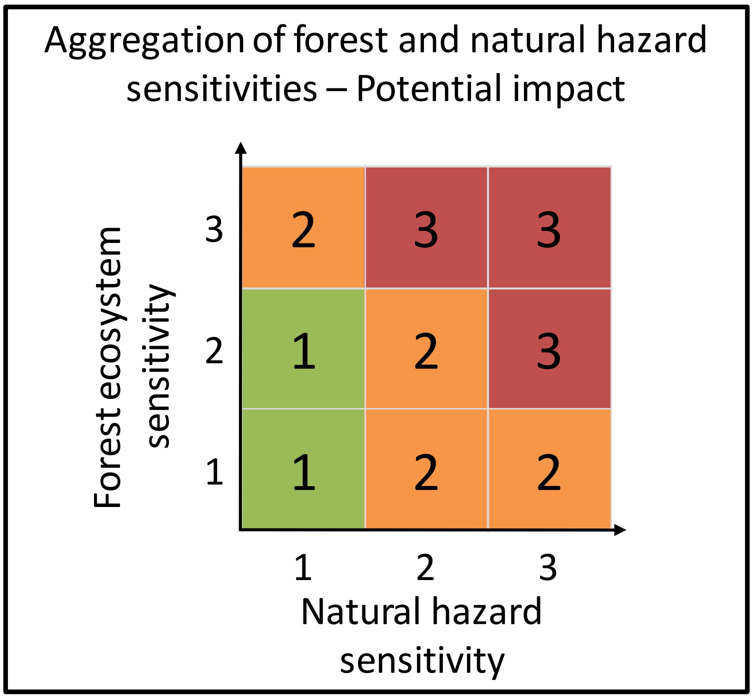


Figure 10: Aggregation of the sensitivity values of forests and hazards to obtain a potential impact estimate (1 = hardly any or small negative potential impact, 2 = medium negative potential impact and 3 = strong negative potential impact).

2.4.4 Adaptive capacity

The next step is the assessment of the adaptive capacity. A static approach has been chosen to estimate the adaptive capacity by evaluating the current situation and assuming this state for the whole assessment period. For this assessment step the following indicators have been selected to generate an estimate of the adaptive capacity in each region:

(i) Forest road network density,

(ii) area share of forest owners <200ha,

(iii) degree of organization and information of these small scale forest owners,

(iv) academic staff of the Bezirksforstinspektionen (BFIs) per 1000 km² forest area,

(v) BFI foresters per 1000 km² forest area,

(vi) academic staff of the Austrian Federal Service for Torrent and Avalanche Control (WLV) per 1000 km² case study area,

(vii) office staff of the WLV per 1000 km² case study area,

(viii) production staff of the WLV per 1000 km² case study area, and

(ix) budget of the WLV per km² case study area.

For each of these indicators a preference function has been assumed to enable an appraisal of each indicator on a cardinal scale from 0 to 1. These preference functions are continuous linear functions except for the indicator regarding the degree of organization and information of small scale forest owners (iii) where a discrete approach is applied (figure 11). In the following the assumptions for each indicator will be described.

(i) For the **density of forest roads** accessible by trucks (rd) in m/ha the preference function (PF) (equation 5) is based on the assumption that the minimal forest road network density allowing forest management is 10 m/ha. As an upper threshold 70 m/ha have been defined.

(ii) With respect to the **area share of small scale forest owners < 200 ha** (sf) in % of the total forest area it is assumed that small shares of small scale forest owners are enhancing the adaptive capacity due to easier coordination and implementation of concerted adaptation whereas big shares are expected to be negative (equation 6).

(iii) As already stated before for the indicator regarding the **degree of organization and information of small scale forest owners** a discrete approach will be applied. The degree of organization and information is seen to be high in regions where small scale forest owners are supported by forest officials on a mandatory basis additionally to the optional support provided by the BFIs and the Landwirtschaftskammer (LWK). The degree of organization and information is assessed to be medium where an optional support of BFIs and the LWK is provided and where voluntary associations of forest owners like Waldwirtschaftsgemeinschaften are existing. A low degree of organization and information refers to regions where such associations are nonexistent and the forest owners are only supported at a voluntary basis by the BFIs and LWK (eq. 7).

(iv) For the indicator dealing with **academic staff in the BFIs** (a_{BFI}) a current range between 1 (lower bound) and 5 academics per 1000 km² forest area (upper bound) has been assumed. With regard to adaptive capacity higher values are of course more preferable (eq. 8).

(v) The same holds true for the number of **BFI foresters** per 1000 km² forest area (f_{BFI}), here a current range for Austrian conditions is assumed from 3 (lower bound) to 9 BFI foresters per 1000 km² forest area (upper bound) (eq. 9).

(vi) A similar reasoning is also applied for the indicators regarding the staff in the management districts of the WLV. With regard to the **academic staff** (a_{WLV}) a current range from 0,5 (lower bound) to 1,5 academics per 1000 km² (upper bound) has been assumed (eq. 10).

(vii) For the **office staff of the WLV** (os_{WLV}) the thresholds are 1,5 (lower bound) and 3 employees per 1000 km² (upper bound) (eq. 11).

(viii) With regard to the **production staff of the WLV** (ps_{WLV}) 5 (lower bound) to 25 workers per 1000 km² (upper bound) have been assumed as current range (eq. 12).

(ix) For the indicator dealing with the **budget of the management districts of the WLV** (b_{WLV}) a possible range between 0 and 5000 Euros per km² has been assumed. With regard to adaptive capacity higher values are of course more preferable (eq. 13).

The preference functions for the used set indicators are displayed in figure 11. These linear functions have been created to provide values between 0 (lower bound) and 1 (upper bound) within the current range of the indicators, as assessed in the latter paragraphs. Values close to 0 indicate small adaptive capacities and values close to 1 indicate high adaptive capacities. Furthermore an indicator focusing on subsidies for the forest sector would also be mostly welcome, but unfortunately no spatially explicit information is available with regard to the distribution of subsidies.

$$PF = 0{,}0167 * rd - 0{,}167 \quad \text{(eq. 5)}$$

$$PF = -0{,}01 * sf - 1 \quad \text{(eq. 6)}$$

Low = 0,25; medium = 0,5; high = 0,75 (eq. 7)

$PF = 0{,}222 * a_{BFI} – 0{,}111$ (eq. 8)

$PF = 0{,}167 * f_{BFI} – 0{,}5$ (eq. 9)

$PF = a_{WLV} – 0{,}5$ (eq. 10)

$PF = 0{,}667 * os_{WLV} – 1$ (eq. 11)

$PF = 0{,}05 * ps_{WLV} – 0{,}25$ (eq. 12)

$PF = 0{,}0002 * b_{WLV}$ (eq. 13)

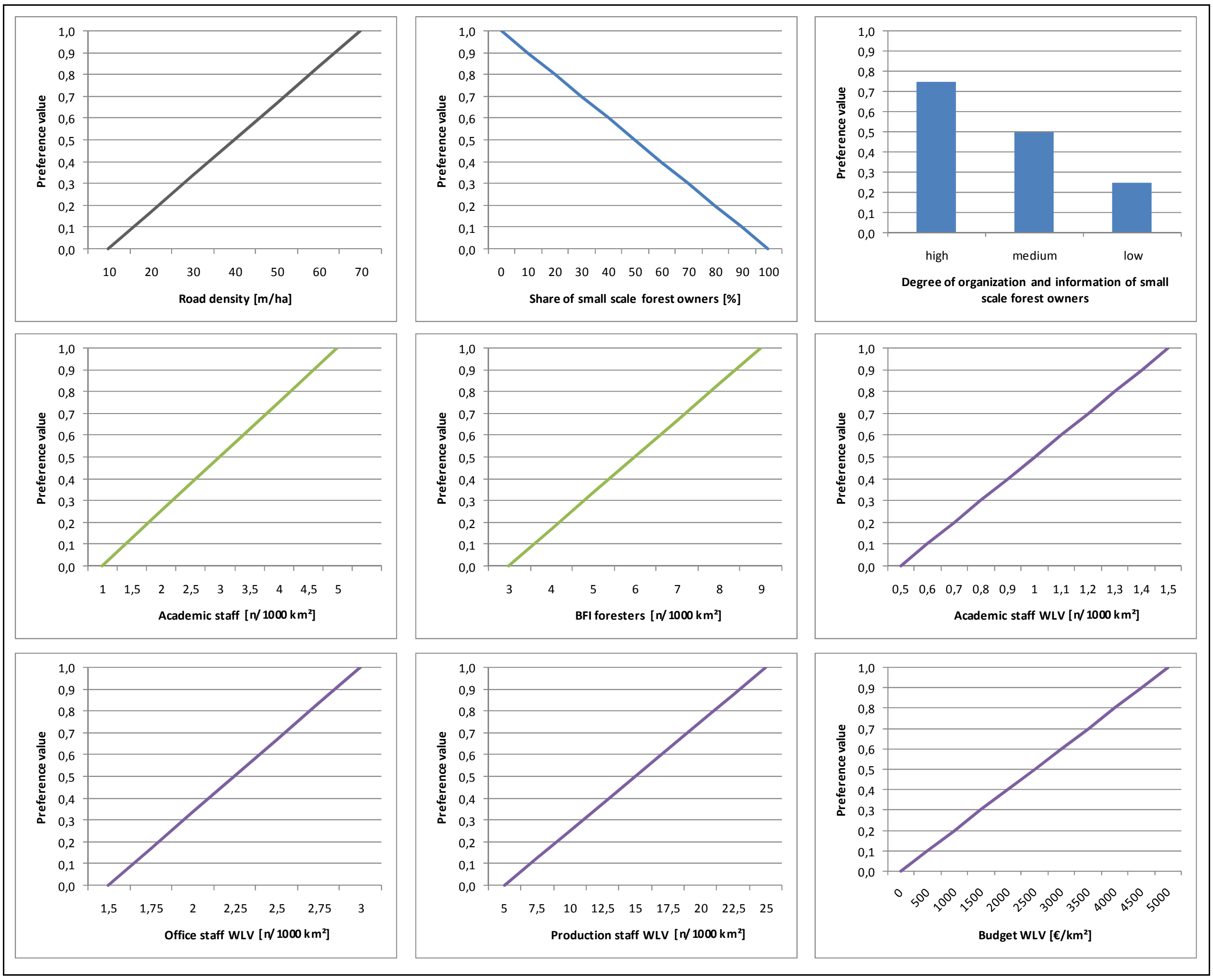


Figure 11: Graphical illustration of the preference functions for the indicators (eq. 5 – 13) used to assess the adaptive capacity.

According to these functions for each indicator a preference value can be calculated. In the following the AHP is used to derive an overall estimate for the adaptive capacity in a region. For each of the indicators a relative weight is calculated via pairwise comparisons of the indicators (table 10).

Table 10: Weights of the indicators derived from pairwise comparisons on Saaty´s ratio scale and used for the assessment of the regional adaptive capacity.

Indicator	Weight
Forest road network density	0,13
Share of forest owners <200 ha	0,19
Degree of organization and information of small scale owners	0,07
Academic staff of the BFIs per 1000 km² forest area	0,15
BFI foresters per 1000 km² forest area	0,07
Academic staff of the WLV per 1000 km²	0,15
Office staff of the WLV per 1000 km²	0,05
Production staff of the WLV per 1000 km²	0,03
Budget of the WLV per km²	0,18
Sum	1,00

Thereafter the preference values for the indicators are aggregated as weighted mean values according to the weights presented in table 10. These cardinal adaptive capacity estimates are now transferred to an ordinal scale allowing an easy aggregation with the potential impacts. Therefore following ordinal classes are generated:

(i) Class 1: low adaptive capacity (cardinal estimate <0,25),

(ii) Class 2: medium adaptive capacity (cardinal estimate between 0,25 and 0,75), and

(iii) Class 3: high adaptive capacity (cardinal estimate >0,75).

To allow compensation of uncertainties the medium class covers twice the range of the first or third class. This conversion procedure providing three adaptive capacity classes at regional level is delineated in figure 12.

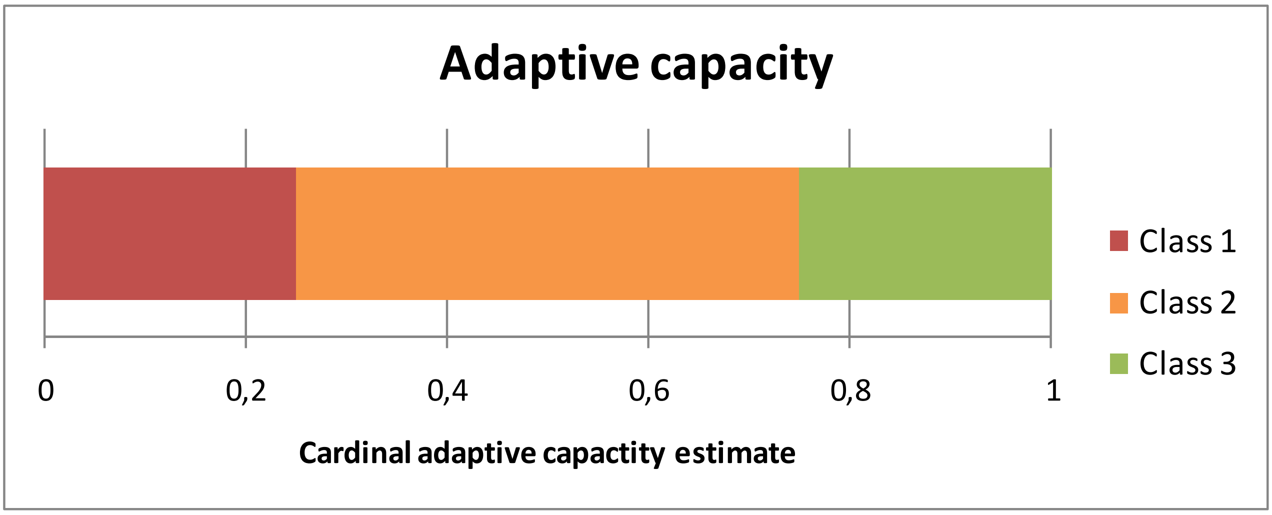


Figure 12: Cardinal adaptive capacity estimates and their conversion into three ordinal classes (1 = low, 2 = medium, 3 = high).

2.4.5 Vulnerability

The final assessment step is the estimation of the regional vulnerability of the protective function against a certain natural hazard. As already stated, vulnerability is a function of potential impact (PI) and adaptive capacity (AC) (cf. equation 1). For this final assessment step a matrix has been developed facilitating a classification of vulnerability of a specific protective function for a given region. Again an ordinal scale is used to classify the vulnerability in low (1), medium (2) and high (3) (figure 13).

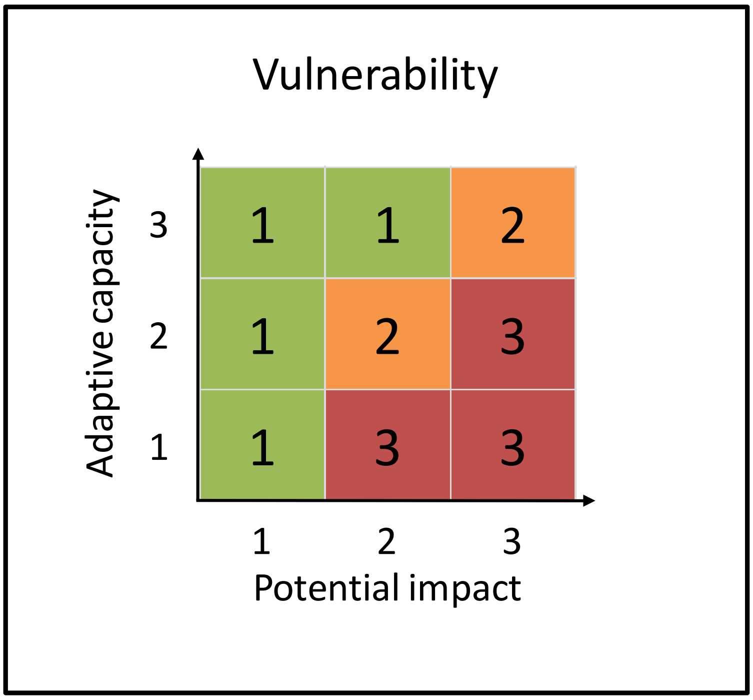


Figure 13: Aggregation of potential impacts and adaptive capacity to obtain the vulnerability of a protective function against a certain hazard. The output classes are low (1), medium (2) and high (3) vulnerability.

The results of this final assessment step are vulnerability classes for each case study and time step with respect to the specific protection provided by forests against one of the five natural hazards regarded.

3 Material

3.1 Literature review

The knowledge base for the vulnerability assessment is created by reviewing scientific articles and project reports. To facilitate an easier handling the different sources have been catalogued with a MS-excel spread sheet. Overall roughly 200 sources have been screened whereas circa 100 have been used in the review.

3.2 Case studies

The vulnerability assessment will be exemplified for three Austrian regions. To provide heterogeneity in terms of topography, geology, geomorphology, forest ecosystems and hazardous processes three regions of rather different characteristics have been chosen. The regarded regions are the Upper Mur Valley, the Upper Inn Valley and the Salzkammergut. These selected regions are matching the management districts of the Austrian Federal Service for Torrent and Avalanche Control (WLV) (figure 14).

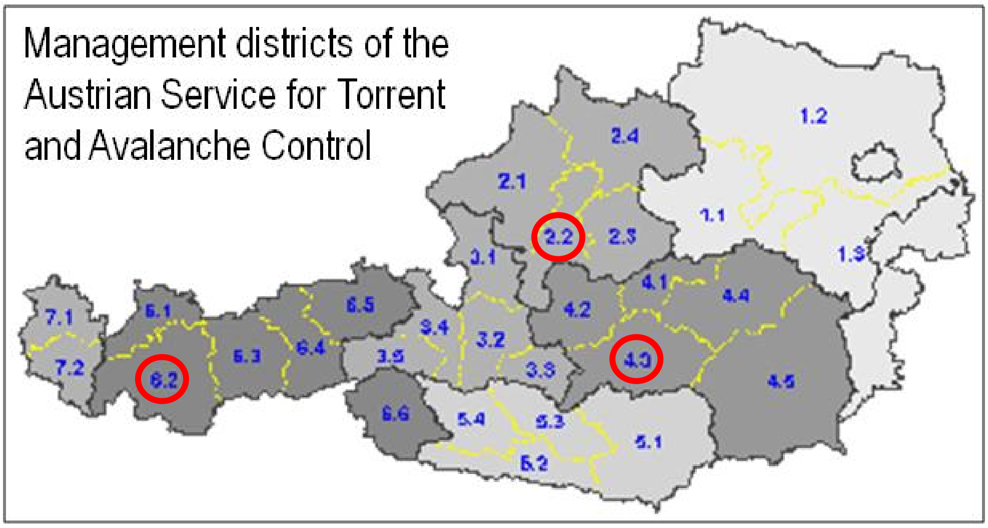


Figure 14: Management districts of the Austrian Federal Service for Torrent and Avalanche Control, the case study regions, highlighted by the red circles, are the Upper Mur Valley (4.3), the Upper Inn Valley (6.2) and the Salzkammergut (2.2) (according to Anonymous, 2009a).

3.2.1 Region A Oberes Murtal

The first case study region is the management district Oberes Murtal of the Austrian Federal Service for Torrent and Avalanche Control. It is situated in the west of Styria and consists of three administrative districts Murau, Judenburg and Knittelfeld covering 3055 km^2. The corresponding Bezirksforstinspektionen (BFIs) are also Murau, Judenburg and Knittelfeld (Anonymous, 2002a).

3.2.1.1 Exposure

After a brief evaluation of the three scenarios (A1B, A2 and B1; Nakicenovic *et al.*, 2000) the A1B scenario was chosen for the vulnerability assessment as it projects the most pronounced changes concerning temperature and precipitation.

The climate change exposure (A1B scenario) for the two assessment time-slices compared to the baseline climate is presented in table 11 for the Upper Mur Valley. The baseline climate of the Upper Mur Valley is comparable to the Upper Inn Valley, but climate change projections are quite different. Remarkably hardly any decrease in precipitation is projected neither for the first time slice nor for the second one for the Upper Mur Valley. This is in strong contrast to the climate change exposures of the two other case study regions where during the second assessment period summer precipitation is decreasing by circa 15 to 20%.

Table 11: Current climate and climate change exposure according to the A1B scenario for the regarded time slices in the Upper Mur Valley.

Climate	**Annual mean temperature** [°C]	**Annual precipitation** [mm]	**Summer precipitation** [mm]	**Winter precipitation** [mm]
Baseline 1971-2000	**4,8**	**966**	**396**	**126**
	Temperature increase [°C]	**Precipitation change** [%]	**Precipitation change** [%]	**Precipitation change** [%]
A1B 2021-2050	**1,0**	**3,7**	**10,8**	**10,9**
A1B 2071-2100	**3,6**	**-1,8**	**-3,5**	**17,3**

3.2.1.2 Forest characteristics

The Upper Mur Valley is characterized by a high forest cover, 189700 ha are forested according to Anonymous (2002a), representing 62% of the case study area. The percentage of forests in yield, roughly 86% (163300 ha), is also high. The share of protective forests is 17,5% (13600 ha protective forests in yield and 19600 ha protective forests without yield). The majority of forests are at altitudes above 1200 m (63%), 30% are at altitudes between 900 and 1200 m and 7% are at altitudes lower than 900 m. With regard to forests in yield Norway spruce (*Picea abies* (L.) Karst.) is the dominating tree species at all elevations according to their area share, as can be seen in table 12. The importance of European larch (*Larix decidua* Mill.) is increasing with altitude and so is also the importance of other coniferous species, which in this case is predominantly *Pinus cembra* L. Broadleaved tree species are quite abundant in lower altitudes but their importance is decreasing with altitude (Anonymous, 1997).

Table 12: Area share of the tree species in forests in yield according to the AFI for the Upper Mur Valley in three altitudinal belts (Anonymous, 1997).

Species		**Altitudinal belt**		
		<900 m	900-1200 m	>1200 m
Spruce	%	**75,5**	**80,7**	**81,9**
Larch	%	**3,2**	**8,5**	**11,9**
Other coniferous	%	**0,0**	**0,0**	**3,9**
Broadleaved	%	**21,3**	**10,9**	**2,3**
Sum	%	**100**	**100**	**100**

With regard to the three development phases (youth, pole and timber stage), needed for further stratification of the case study, the assumptions presented in table 1 are used to approximate development phases from the age class information provided by the AFI. The observed and assumed future shares of development phases for the Upper Mur Valley are presented in table 13. To estimate future area shares a simple age class model has been applied presuming rotation periods for each altitudinal zone (table 14). This calculation is based on information of the AFI period 1992 - 1996 (Anonymous, 1997) as the freely available data for the period 2000 – 2002 (Anonymous, 2002a) is unfortunately less detailed. An exhaustive tabulation of the area shares with respect to tree species and altitudinal zones is presented in the appendix 0 in combination with the assessment of states and forest responses.

Table 13: Observed and assumed future area shares of the three development phases in the Upper Mur Valley according to Anonymous (1997).

Development phase	1995	2035	2085
Youth	20%	13%	21%
Pole stage	35%	31%	25%
Timber stage	45%	56%	54%

Table 14: Rotation periods assumed for the three altitudinal stages in the case study regions.

Altitudinal zone	Oberes Murtal	Oberes Inntal	Salzkammergut
Low (< 900 m)	90 years	100 years	90 years
Medium (900 – 1200 m)	100 years	110 years	100 years
High (> 1200 m)	120 years	140 years	120 years

The annual increment ($m^3*ha^{-1}*a^{-1}$) in forests in yield is depicted in table 15 for regarded tree species (according to Anonymous, 1997).

Table 15: Annual increment (forests in yield) of regarded tree species in the Upper Mur Valley (according to Anonymous, 1997).

Species	Increment [$m^3*ha^{-1}*a^{-1}$]
Picea abies	10,0
Larix decidua	9,9
Other coniferous species	3,5
Broadleaved species	5,7

According to the AFI the percentage of damaged individuals is relatively high, 40% of all stems are damaged by bark-peeling, rock fall, harvesting activities or fraying and beating (Anonymous, 1997). As an approximation of mortality the share of damaged timber in annual felling provided by the Holzeinschlagsmeldung is used, unfortunately these data are only available at federal and provincial level (table 16) a more detailed spatial resolution would be welcome. The Styrian average for the last eight years is 38% of damaged timber in the annual felling, a quite high percentage. The development during these years is depicted in figure 15 in comparison with Tyrol and Upper Austria (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Table 16: Share of damaged timber in the annual felling according to the Holzeinschlagsmeldung for Styria (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Year	Share of damaged timber
2001	21,8%
2002	20,2%
2003	52,1%
2004	37,6%
2005	31,4%
2006	29,0%
2007	37,1%
2008	77,3%
Average	**38,3%**

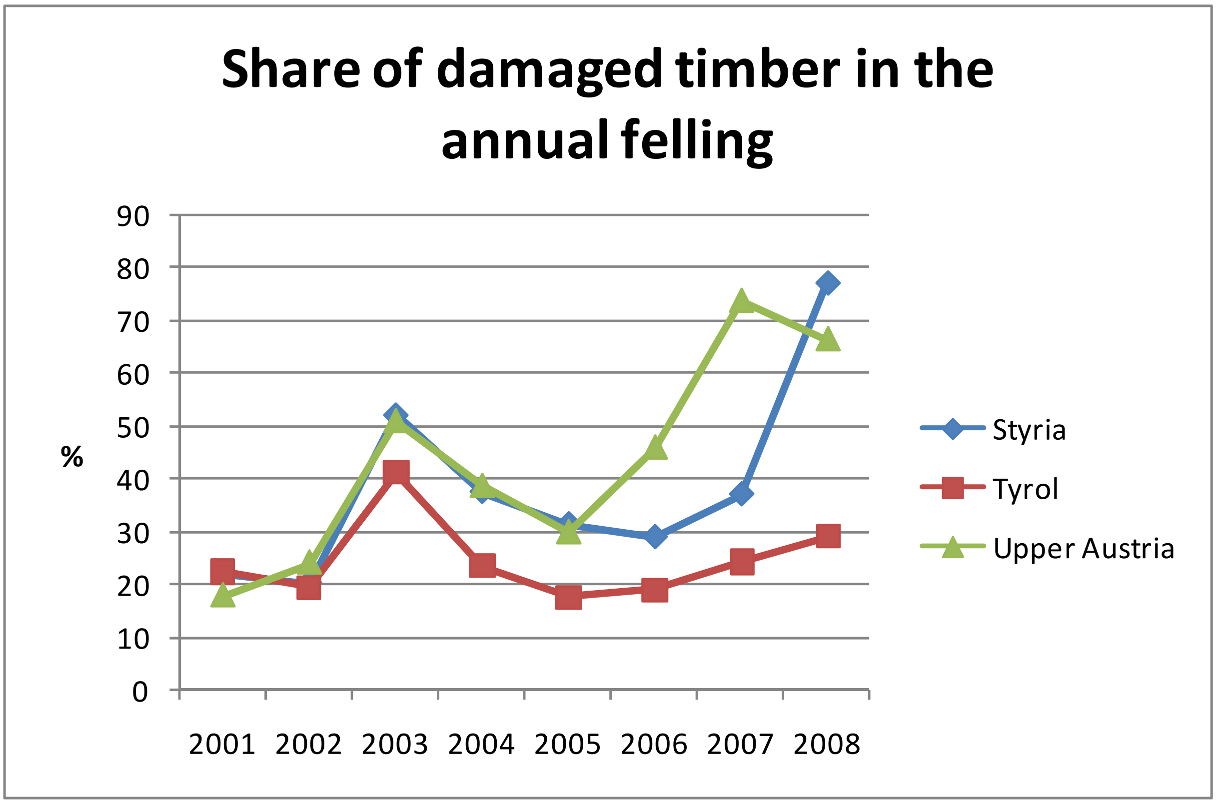


Figure 15: Development of the percentage of damaged timber in the annual felling (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

The accessibility of forest stands is at a high level as the forest road network density is 60.7 m/ha, ranking the Upper Mur Valley first in the comparison with the other regions. The share of small scale forest owners (<200 ha) sums up to 63.3% according to the AFI, this value is significantly larger than in the other case study regions (Anonymous, 1997 and 2002a). The information and organization of these small scale forest owners is judged to be on a medium level, as there is no legally binding support of forest authorities like in Tyrol and Vorarlberg, forest owners are supported by the Landwirtschaftskammer and the BFIs on a less mandatory basis. The three BFIs responsible for the Upper Mur Valley are employing 3 forest academics and 10 foresters (Land Steiermark, 2009). The following table 17 is summing up the information needed as input for the assessment of the adaptive capacity with regard to forest characteristics.

Table 17: Values for the forest specific indicators used for the assessment of the regional adaptive capacity of the Upper Mur Valley.

Indicator	Value
Forest road network density	60,7 m/ha
Area share of small scale forest owners (<200ha)	63,3%
Degree of organization and information of small scale owners	medium
Academic staff of the BFIs per 1000 km² forest area	1,58 n/1000 km²
BFI foresters per 1000 km² forest area	5,27 n/1000 km²

3.2.1.3 Natural hazard and management district characteristics

During the interviews the regional managers of the management districts of the Austrian Federal Service for Torrent and Avalanche Control were asked to rank the natural hazardous processes according to their importance during the last decades. For the Upper Mur Valley the hazards have been ranked as follows (Pöllinger, 2009, personal communication):

1. Flooding,
2. Debris flow,
3. Rock fall,
4. Avalanche, and
5. Landslide.

Furthermore the current state of the processes regarding frequency (cf. table 8) and magnitude (cf. table 9) has been estimated by the regional managers (table 18). These estimates are valuable input parameters for the sensitivity assessment and are not altered due to a lack of regional experience.

Table 18: Current state of frequency and magnitude of the regarded natural hazards according to the local expertise of the regional manager of the management district Oberes Murtal (for frequency: class 1 = seldom, class 2 = frequent, class 3 = very frequent; for magnitude: class 1 = small, class 2 = medium, class 3 = large) (Pöllinger, 2009, personal communication).

Natural hazard	Frequency	Magnitude
Flooding	**2**	**2**
Debris flow	**2**	**2**
Landslide	**1**	**1**
Rock fall	**2**	**1**
Avalanche	**1**	**1**

Additionally the regional managers were asked to estimate the development of frequency and magnitude (cf. table 3) of these natural hazards for the second assessment period (2071 – 2100) (table 19). These estimates are taken into account when assessing the response of the natural hazards, but contrary to the state estimates these values are not direct input parameters. The estimates of the regional managers are taken into account as a very valuable input in terms of local experience but they are compared and extended with literature knowledge and thereafter used as input for the sensitivity assessment.

Table 19: Estimates of the regional manager about the development of frequencies and magnitudes for the second assessment period (2071 – 2100) (1 = positive response, 2 = hardly any positive or negative response, 3 = slight negative response, 4 = moderate negative response and 5 = strong negative response) (Pöllinger, 2009, personal communication).

Natural hazard	Frequency	Magnitude
Flooding	**4**	**4**
Debris flow	**4**	**4**
Landslide	**3**	**3**
Rock fall	**3**	**3**
Avalanche	**2**	**2**

The management district of the Austrian Federal Service for Torrent and Avalanche Control Oberes Murtal manages an area of 3055 km² and has 33 employees. The staff is structured in two university graduates, six further white collar workers and 25 blue collar workers, ranking the management district “Oberes Murtal” last in the comparison with the other regarded management districts. The budget of the management district was estimated to be roughly 3,5 million Euros as an average for the last decade (Pöllinger, 2009, personal communication). The following table 20 is summing up the information needed as input for the assessment of the adaptive capacity with regard to the characteristics of the management district Oberes Murtal of the WLV.

Table 20: Management district specific values for the indicators used to assess the regional adaptive capacity of the Upper Mur Valley (according to Pöllinger, 2009, personal communication).

Indicator	Value
Academic staff of the WLV per 1000 km² case study area	0,65 n/1000 km²
Office staff of the WLV per 1000 km² case study area	1,96 n/1000 km²
Production staff of the WLV per 1000 km² case study area	8,18 n/1000 km²
Budget of the WLV per km² case study area	980 €/km²

3.2.1.4 Geology

The case study region of the Upper Mur Valley belongs principally to the Austroalpine Crystalline Complexes and to the Paleozoic. Gneiss and other metamorphic rocks are dominant (cf. figure 16; Egger *et al.*, 1999).

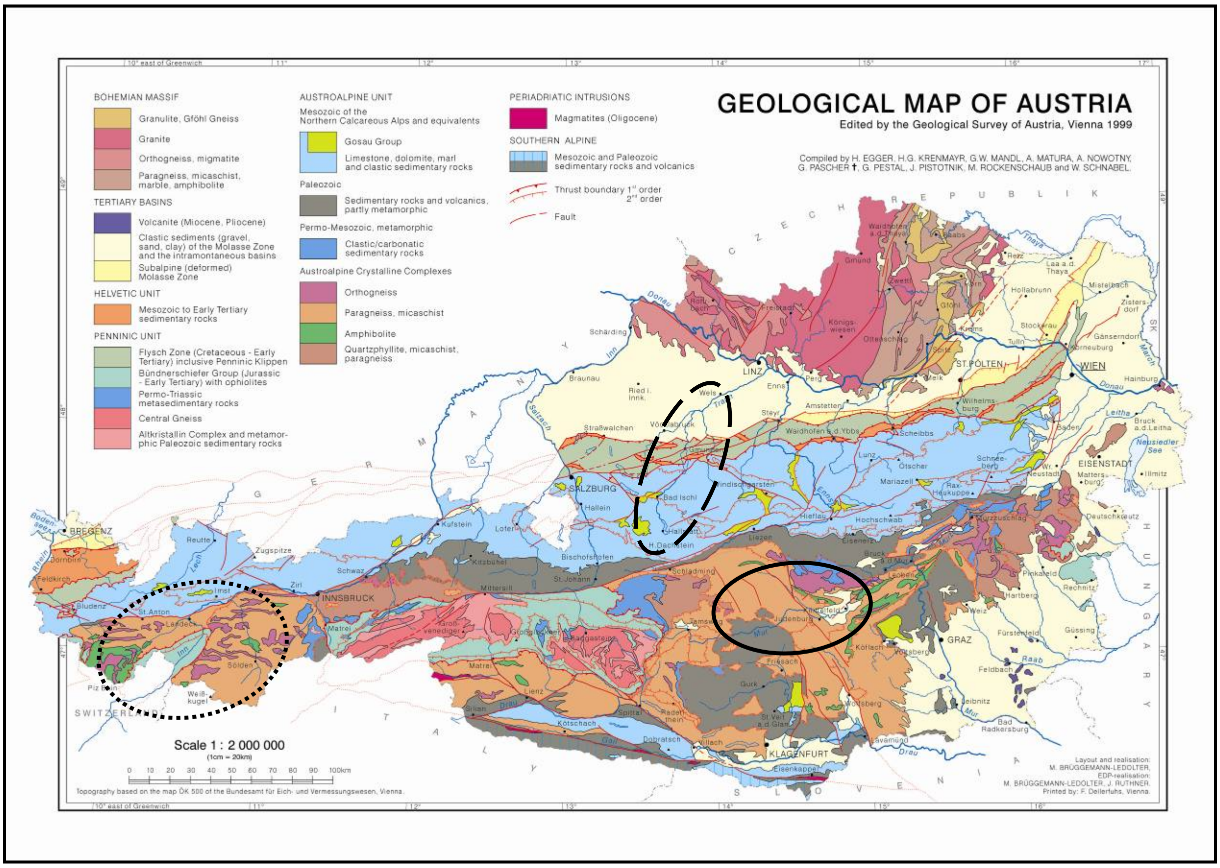


Figure 16: Geological map of Austria (Egger *et al.*, 1999) with highlighted case studies (solid line = Upper Mur Valley, dotted line = Upper Inn Valley and dashed line = Salzkammergut).

3.2.2 Region B Oberes Inntal

The management district Oberes Inntal of the Austrian Federal Service for Torrent and Avalanche Control is situated in the west of Tyrol and consists of the administrative districts Landeck and Imst covering 3320 km². The Bezirksforstinspektionen according to the AFI are Landeck, Imst, Ried im Oberinntal and Silz (Anonymous, 1997 and 2002).

3.2.2.1 Exposure

The climate change exposure (A1B scenario, Nakicenovic *et al.*, 2000) for the two assessment time-slices compared to the baseline climate is presented in table 21 for the Upper Inn Valley. In general the baseline climate values for the Upper Inn Valley are comparable to the climate values of the Upper Mur Valley, but the climate change projections are showing different trends. Temperature increases are most pronounced in this case study area, and furthermore according to the projections for the second assessment period this region will suffer strong decreases in precipitation during the summer months July, August and September where precipitation will drop by roughly -20% to 271 mm. This trend is stronger than in the two other case study areas, where for the Salzkammergut roughly -15% are projected and for the Upper Mur Valley where hardly any decrease is expected for the summer months.

Table 21: Current climate and climate change exposure according to the A1B scenario for the regarded time slices in the Upper Inn Valley.

Climate	**Yearly mean temperature** [°C]	**Annual precipitation** [mm]	**Summer precipitation** [mm]	**Winter precipitation** [mm]
Baseline 1971-2000	**4,3**	**954**	**346**	**173**
	Temperature increase [°C]	**Precipitation change** [%]	**Precipitation change** [%]	**Precipitation change** [%]
A1B 2021-2050	**1,1**	**1,9**	**0,7**	**6,2**
A1B 2071-2100	**4,1**	**-7,9**	**-21,1**	**10,3**

3.2.2.2 Forest characteristics

According to the AFI forest covers 103900 ha of the Upper Inn Valley which is a share of 31,3% of the total area. 64,4% (66900 ha) of the forest area are classified as forests in yield. These are considerably lower values compared to the Upper Mur Valley. Furthermore the share of protective forests is significantly larger, 55,6% (57700 ha) of the forest area is classified as protective forests (22400 ha protective forests in yield and 35300 protective forests without yield) (Anonymous, 2002a). The vast majority of forests are at altitudes above 1200 m (75%), 17% are at altitudes between 900 and 1200 m and 9% are at altitudes lower than 900 m. In the forests in yield *Picea abies* is the dominating tree species in the lower and upper elevation stages whereas in the middle altitudinal belt *Pinus sylvestris* L. (44,9%) shares more area than Norway spruce (cf. table 22). In the lower and upper altitudinal belts Scots pine (*Pinus sylvestris* L.) is not as important (~7%). The area share of *Larix decidua* is slightly increasing with altitude from circa 10 to 13%. Other coniferous species (especially *Pinus cembra*) are only relevant in the higher altitudes and the share of broadleaved species is strongly decreasing with altitude (Anonymous, 1997).

Table 22: Area share of the tree species in forests in yield according to the AFI for the Upper Inn Valley in three altitudinal belts

Species		Altitudinal belt		
		<900 m	900-1200 m	>1200 m
Spruce	%	**65,4**	**38,8**	**67,8**
Larch	%	**9,6**	**11,2**	**13,2**
Scots pine	%	**7,7**	**44,9**	**7,3**
Other coniferous	%	**0,0**	**0,0**	**9,5**
Broadleaved	%	**17,3**	**5,1**	**2,3**
Sum	%	**100**	**100**	**100**

With regard to the three development phases (youth, pole and timber stage), needed for further stratification of the case study assumptions presented in table 1 have been made to convert age classes into development phases. The observed and assumed future shares of development phases for the Upper Inn Valley are presented in table 23. To estimate future area shares a simple age class model has been applied presuming rotation periods for each altitudinal zone (table 14). This calculation is based on information of the AFI period 1992 - 1996 (Anonymous, 1997). An exhaustive tabulation of the area shares with respect to tree species and altitudinal zones is presented in Appendix 0 in combination with the assessment of states and forest responses.

Table 23: Observed and assumed future area shares of the three development phases in the Upper Inn Valley according to Anonymous (1997).

Development phase	1995	2035	2085
Youth	13%	7%	9%
Pole stage	23%	55%	12%
Timber stage	64%	37%	79%

The annual increment ($m^3*ha^{-1}*a^{-1}$) in forests in yield is depicted in table 24 for regarded tree species (according to Anonymous, 1997).

Table 24: Annual increment (forests in yield) of regarded tree species in the Upper Inn Valley (according to Anonymous, 1997)

Species	Increment [$m^3*ha^{-1}*a^{-1}$]
Picea abies	6,3
Larix decidua	6,5
Pinus sylvestris	3,3
Other coniferous species	4,3
Broadleaved species	7,5

According to the AFI 39% of the stems are damaged by bark-peeling, rock fall, harvesting activities or fraying and beating. As an approximation of mortality the share of damaged timber in annual felling provided by the Holzeinschlagsmeldung is used (table 25). The Tyrolean average for the last eight years is 25%, compared to the other provinces this value is rather low. The development during these years is depicted in figure 15 in comparison with Styria and Upper Austria (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Table 25: Share of damaged timber in the annual felling according to the Holzeinschlagsmeldung for Tyrol (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Year	Share of damaged timber
2001	22,4%
2002	19,5%
2003	41,2%
2004	23,5%
2005	17,6%
2006	19,0%
2007	24,3%
2008	29,1%
Average	**24,6%**

The forest road network density is 37,4 m/ha which is the lowest value for all tree regions. The share of small scale forest owners is 29,6% and these forest owners are judged to have a high degree of organization and information as in Tyrol the support of the local forest authorities is mandatory (Anonymous, 1997 and 2002a). The BFIs responsible for the Upper Inn Valley are employing 4 forest academics and 8 foresters (Land Tirol, 2009a, 2009b). The following table 26 is summing up the information needed as input for the assessment of the adaptive capacity with regard to forest characteristics.

Table 26: Values for the forest specific indicators used for the assessment of the regional adaptive capacity of the Upper Inn Valley.

Indicator	Value
Forest road network density	37,4 m/ha
Area share of small scale forest owners (<200ha)	29,6%
Degree of organization and information of small scale owners	High
Academic staff of the BFIs per 1000 km² forest area	3,58 n/1000 km²
BFI foresters per 1000 km² forest area	7,70 n/1000 km²

3.2.2.3 Natural hazard and management district characteristics

According to the estimate of the regional manager the natural hazards have been ranked according to their importance as follows (Weber, 2009, personal communication):

1. Avalanche,
2. Landslide,
3. Flooding and debris flow, and
4. Rock fall.

The current state of the processes regarding the indicators frequency (cf. table 8) and magnitude (cf. table 9) as assessed by the regional managers is presented in table 27.

Table 27: Current state of frequency and magnitude of the regarded natural hazards according to the local expertise of the regional manager of the management district Oberes Inntal (for frequency: class 1 = seldom, class 2 = frequent, class 3 = very frequent; for magnitude: class 1 = small, class 2 = medium, class 3 = large) (Weber, 2009, personal communication).

Natural hazard	Frequency	Magnitude
Flooding	**2**	**2**
Debris flow	**2**	**3**
Landslide	**2**	**2**
Rock fall	**3**	**2**
Avalanche	**3**	**3**

The regional manager's estimates for the development of frequency and magnitude (cf. table 3) until the second assessment period (2071 - 2100) are depicted in table 28.

Table 28: Estimates of the regional manager about the development of frequencies and magnitudes for the second assessment period (2071 – 2100) (1 = positive response, 2 = hardly any positive or negative response, 3 = slight negative response, 4 = moderate negative response and 5 = strong negative response) (Weber, 2009, personal communication).

Natural hazard	Frequency	Magnitude
Flooding	**5**	**4**
Debris flow	**5**	**4**
Landslide	**4**	**4**
Rock fall	**3**	**3**
Avalanche	**5**	**5**

The management district of the Austrian Federal Service for Torrent and Avalanche Control Oberes Inntal manages an area of 3320 km² and has 78 employees. The personnel is structured in four university graduates, nine further white collar workers and 65 blue collar workers in comparison with the other case study regions the management district Oberes Inntal is clearly the one with the highest number of personnel. The yearly budget is roughly ten million Euros in average over the last decade also indicating the first rank in comparison with the other two regions (Weber, 2009, personal communication). The following table 29 is summing up the information needed as input for the assessment of the adaptive capacity with regard to the characteristics of the management district Oberes Inntal.

Table 29: Values for the management district specific indicators used for the assessment of the regional adaptive capacity of the Upper Inn Valley (according to Weber, 2009, personal communication).

Indicator	Value
Academic staff of the WLV per 1000 km² case study area	1,20n/1000 km²
Office staff of the WLV per 1000 km² case study area	2,71 n/1000 km²
Production staff of the WLV per 1000 km² case study area	19,58 n/1000 km²
Budget of the WLV per km² case study area	3010 €/km²

3.2.2.4 Geology

The case study region Oberes Inntal consists of three geologic units the Austroalpine Crystalline Complex and the Penninic unit which are dominated by gneiss and other metamorphic rocks and the Mesozoic of the Northern Calcareous Alps dominated by limestone and dolomite (cf. figure 16; Egger *et al.*, 1999).

3.2.3 Region C Salzkammergut

The management district Salzkammergut of the Austrian Federal Service for Torrent and Avalanche Control is situated in the south of Upper Austria and is responsible for the administrative districts Gmunden, Wels Land and Wels Stadt summing up to 2195 km². The respective Bezirksforstinspektionen are Gmunden and Wels (Anonymous, 1997 and 2002a).

3.2.3.1 Exposure

The climate change exposure (A1B scenario; Nakicenovic *et al.*, 2000) for the two assessment time-slices in comparison to the baseline climate is presented in table 30 for the Salzkammergut. In general the baseline climate of the Salzkammergut case study area is warmer and moister compared to the two other regions. The temperature increases expected for this region is not as pronounced as for the other regions and the projections for changes in precipitation do also differ. For the first assessment period annual precipitation is projected to increase by 12% whereas the second period is expected to receive roughly the same amount of precipitation like under current conditions, but with changed seasonality. In the second period the summer months are expected to get drier by roughly 15% whereas the winter months December, January and February are projected to receive more precipitation.

Table 30: Current climate and climate change exposure according to the A1B scenario for the regarded time slices in the Salzkammergut.

Climate	**Yearly mean temperature** [°C]	**Annual precipitation** [mm]	**Summer precipitation** [mm]	**Winter precipitation** [mm]
Baseline 1971-2000	**7,1**	**1469**	**504**	**297**
	Temperature increase [°C]	**Precipitation change** [%]	**Precipitation change** [%]	**Precipitation change** [%]
A1B 2021-2050	**0,7**	**12,0**	**8,6**	**6,2**
A1B 2071-2100	**3,4**	**1,1**	**-15,8**	**13,3**

3.2.3.2 Forest characteristics

According to the AFI forest covers 104300 ha of the Salzkammergut case study region, this are 47,5% of the total area. Of these 104300 ha 75,8% percent are classified as forests in yield (79100 ha). The percentage of protective forests is 36,7% (13000 ha protective forests in yield and 21600 ha protective forests without yield) (Anonymous, 2002a). Contrary to the other case study regions the majority (66%) of forests in yield is located at altitudes lower than 900m, 26% are at altitudes between 900 and 1200 m and only 7% are at altitudes higher than 1200 m. The area share of the tree species in the forests in yield is presented in table 31. *Picea abies* is the dominating tree species in all elevation stages. Beech (*Fagus sylvatica* L.) has a prominent share at lower and middle altitudes and the share decreases significantly for the higher altitudes. Other coniferous species share between 4 and 8 percent and other broadleaved species have a share of roughly 13% in the region below 900 m and their importance strongly decreases at the middle and higher elevation stages (Anonymous, 1997 and 2002).

Table 31: Area share of the tree species in forests in yield according to the AFI for the Salzkammergut in three altitudinal belts.

Species		**Altitudinal belt**		
		<900 m	900-1200 m	>1200 m
Spruce	%	**55,0**	**51,3**	**83,3**
Beech	%	**27,9**	**39,6**	**11,1**
Other coniferous	%	**4,4**	**7,6**	**3,7**
Other broadleaved	%	**12,7**	**1,5**	**1,9**
Sum	%	**100**	**100**	**100**

With regard to the three development phases (youth, pole and timber stage), needed for further stratification of the case study assumptions presented in table 1 have been made to convert age classes into development phases. The observed and assumed future shares of development phases for the Salzkammergut are presented in table 32. To estimate future area shares a simple age class model has been applied assuming rotation periods for each altitudinal zone (table 14). This calculation is based on information of the AFI period 1992 - 1996 (Anonymous, 1997). An exhaustive tabulation of the area shares with respect to tree species and altitudinal zones is presented in appendix 0 in combination with the assessment of states and forest responses.

Table 32: Observed and assumed future area shares of the three development phases in the Salzkammergut according to Anonymous (1997).

Development phase	1995	2035	2085
Youth	21%	12%	21%
Pole stage	22%	37%	20%
Timber stage	57%	50%	59%

The annual increment ($m^3*ha^{-1}*a^{-1}$) in forests in yield is depicted in table 33 for the regarded tree species (according to Anonymous, 1997).

Table 33: Annual increment (forests in yield) of regarded tree species in the Salzkammergut (according to Anonymous, 1997).

Species	Increment [$m^3*ha^{-1}*a^{-1}$]
Picea abies	9,0
Fagus sylvatica	5,7
Other coniferous species	13,0
Other broadleaved species	8,5

With 35,4% damaged stems due to bark peeling, rock fall, harvesting activities or fraying and beating the Salzkammergut case study region trees are the least damaged in this comparison. But contrary to that the share of damaged timber in the annual felling used as an approximation of mortality is the largest in comparison with the other provinces. The Upper Austrian average for the last eight years is 43% (table 34). The development during these years is depicted in figure 15 in comparison with Styria and Tyrol (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Table 34: Share of damaged timber in the annual felling according to the Holzeinschlagsmeldung for Upper Austria (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Year	Share of damaged timber
2001	17,9%
2002	24,1%
2003	50,9%
2004	38,6%
2005	29,9%
2006	45,9%
2007	73,7%
2008	66,4%
Average	**43,4%**

The forest road network density is 45,1 m/ha and thus between the two other case study areas. The share of small scale forest owners is 26,7% ranking the Salzkammergut as the region with the lowest small scale forest owners share (Anonymous, 2002a). The degree of organization is judged to be medium like for the Upper Mur Valley (cf. page 31). The BFIs responsible for the case study region Salzkammergut are employing 2 forest academics and 4 foresters (Land Oberösterreich, 2009). The following table 35 is summing up the information needed as input for the assessment of the adaptive capacity with regard to forest characteristics.

Table 35: Values for the forest specific indicators used for the assessment of the regional adaptive capacity of the Salzkammergut.

Indicator	Value
Forest road network density	45,1 m/ha
Area share of small scale forest owners (<200ha)	26,7%
Degree of organization and information of small scale owners	Medium
Academic staff of the BFIs per 1000 km² forest area	1,92 n/1000 km²
BFI foresters per 1000 km² forest area	3,84 n/1000 km²

3.2.3.3 Natural hazard and management district characteristics

The regarded natural hazards are of equal importance for according to the regional manager of the Austrian Federal Service of Torrent and Avalanche Control in his management district (Schiffer, 2009, personal communication). When asked about the current state of frequency (cf. table 8) and magnitude (cf. table 9) of regarded hazards following estimates (table 36) were obtained.

Table 36: Current state of frequency and magnitude of the regarded natural hazards according to the local expertise of the regional manager of the management district Salzkammergut (for frequency: class 1 = seldom, class 2 = frequent, class 3 = very frequent; for magnitude: class 1 = small, class 2 = medium, class 3 = large) (Schiffer, 2009, personal communication).

Natural hazard	Frequency	Magnitude
Flooding	**2**	**2**
Debris flow	**1**	**2**
Landslide	**2**	**3**
Rock fall	**3**	**2**
Avalanche	**2**	**2**

Additionally to the estimates for the current state also estimates for the future development of frequency and magnitude (cf. table 3) of the regarded hazards have been assessed during the interview with the regional manager. In table 37 the estimates for the second assessment period (2071 – 2100) are depicted.

Table 37: Estimates of the regional manager about the development of frequencies and magnitudes for the second assessment period (2071 – 2100) (1 = positive response, 2 = hardly any positive or negative response, 3 = slight negative response, 4 = moderate negative response and 5 = strong negative response) (Schiffer, 2009, personal communication).

Natural hazard	Frequency	Magnitude
Flooding	**2**	**2**
Debris flow	**2**	**2**
Landslide	**4**	**4**
Rock fall	**4**	**4**
Avalanche	**5**	**5**

The management district Salzkammergut of the Austrian Federal Service for Torrent and Avalanche Control is responsible for 2195 km². It has 44 employees which are structured in three university graduates, six further white collar workers and 35 blue collar workers. The yearly average budget is roughly three million Euros, but because of a very virulent landslide the budget of the year 2008 reached roughly 12 million Euros (Schiffer, 2009, personal communication). This fact shows that the budget is not a very reliable indicator for e.g. the assessment of the adaptive capacity as it can be easily influenced by critical demand. Table 38 is summing up the information needed as input for the assessment of the adaptive capacity with regard to characteristics of the management district Salzkammergut.

Table 38: Values for the management district specific indicators used for the assessment of the regional adaptive capacity of the Salzkammergut (according to Schiffer, 2009, personal communication).

Indicator	Value
Academic staff of the WLV per 1000 km² case study area	1,37 n/1000 km²
Office staff WLV per 1000 km² case study area	2,73 n/1000 km²
Production staff WLV per 1000 km² case study area	15,95 n/1000 km²
Budget of the WLV per km² case study area	1370 €/km²

3.2.3.4 Geology

The geologic units prevalent in the case study region Salzkammergut are the Mesozoic of the Northern Calcareous Alps with limestone and dolomite, the Penninic unit with the Flysch Zone and Tertiary basins with clastic sediments of the Molasse Zone (cf. figure 16; Egger *et al.*, 1999)

4 Results

4.1 Literature review

4.1.1 System sensitivities

4.1.1.1 Forest ecosystem

The forest ecosystem sensitivities will be classified in five groups for an easier handling during the literature review as well as in the vulnerability assessment. The results of the literature review are structured in changes in:

(i) growth,
(ii) species composition,
(iii) mortality,
(iv) regeneration, and
(v) tree line.

Growth

Changes in temperature, precipitation and CO_2 concentration are influencing forest ecosystems either individually or in combination. Several empirical studies show changes in growth due to climatic changes observed during the last centuries. In currently temperature limited regions growth stimulation due to temperature increases can be expected as shown for *Picea abies* for the last 15 years in a subalpine environment by Bolli *et al.* (2007). A study by Rolland *et al.* (1998) in the French Alps did conclude on similar patterns by showing growth increases to be strongest in the in the coldest regions. This is in accordance with studies on growth increases of *Pinus cembra* in the Austrian and Swiss Alps where the increases have been related to warming temperatures (Paulsen *et al.*, 2000; Vittoz *et al.*, 2008). It has been found that at the end of the 20th century the basal area increment of trees at the tree line used to be as large as the increment of sites situated 250 meters lower in the early 19th century (Paulsen *et al.*, 2000).

Based on data of the Austrian Forest Inventory Hasenauer (2000) is reporting a general increase of growth for *Picea abies.* By means of a simulation study temperature increases and thus elongated growing seasons were found to be the main causes for this trend (Hasenauer *et al.*, 1999; Hasenauer, 2000).

Nevertheless limitations are also reported with respect to temperature increase induced growth stimulation. Temperature correlated growth increases can be inflicted by drought stress as shown by Büngten *et al.* (2006) analyzing subalpine *Picea abies* chronologies. Further limits to a temperature increase related relaxation of the current environmental harshness in subalpine regions are presented by Oberhuber (2004) and Oberhuber *et al.* (2008) conducting studies on Mt. Patscherkofel in Tyrol. Warming related earlier root or shoot growth might reduce late frost hardiness of *Pinus cembra*. The hot and dry summers in the 1990s caused drought stress particularly at south-facing slopes which underlines the importance of orientation and slope in mountain ecosystems (Oberhuber, 2004).

Growth decreases have been observed too, mainly in lower lying regions of the Alps where sites are water limited. Drought is strongly impairing growth as shown by Eilmann *et al.* (2006) for *Pinus sylvestris* L. and *Quercus pubescens* Willd. in an inner alpine dry valley in the Valais (Switzerland). Similar observations have been found for *Picea abies* and *Pinus sylvestris* for other inner alpine environments like for example the Inn Valley. The summer heat wave of 2003, for instance, resulted in radial growth reductions due to a stop in cambial activity (Pichler and Oberhuber, 2007).

Effects of increased atmospherical CO_2 levels on tree vitality and growth are not thoroughly understood yet. A Swiss in situ CO_2 enrichment experiment at the tree line led to increased growth of *Larix decidua*, whereas growth of *Pinus uncinata* Mill. ex Mirb. did not increase (Handa *et al.*, 2005; 2006). The authors conclude that “[…] *the expected changes in growth of these tree line trees with improving carbon availability as atmospheric* CO_2 *continues to increase will thus depend on both the interplay between biotic and abiotic processes, and the species or tree functional types involved* […]” (Handa *et al.*, 2005; p.1288).

Climate change effects on growth have also been subject to a variety of simulation studies. A study conducted for the French Alps assuming doubled CO_2

concentrations is finding growth increases for conifers at high altitudes from 1600 to 2200 m a.s.l. due to a warming related extension of the growing season. An important statement is that growth reactions either positive or negative tend to be stronger the closer a species is to the limits of its natural range (Keller *et al.*, 2000).

Conducting large scale scenario model simulations, Schelhaas *et al.* (2002) found forest growth to increase in Switzerland by 2 m^3*ha^{-1} and year until 2048 by assuming temperature to increase by 1,5°C, slight increases in precipitation and climate change induced changes in the disturbance regimes.

For an inner alpine basin in Carinthia Lexer *et al.* (2006) conducted a simulation study featuring *Picea abies*, *Fagus sylvatica* and *Quercus robur* L. For the two deciduous species growth increased under all investigated climate scenarios, whereas the productivity of *Picea abies* slightly declined under warmer and drier conditions.

Species composition

Climate change has the ability to change the species composition of forest ecosystems but changes in species composition are hard to observe in the intensively managed forests of the Alps, where climatic effects on composition and structure are overridden by silvicultural management. Therefore the concept of natural potential vegetation (PNV) is used as a standard approach to describe projected climate change effects on species composition.

A simulation study focusing on species distribution and richness was conducted by Kienast *et al.* (1998) for Switzerland. Assuming warmer temperatures without changes in precipitation the results indicate a shift from relatively species poor communities to rich ones due to the range expansion of diverse broadleaved dominated forest communities. Oak-hornbeam (*Carpinion-betuli*, *Quercion robori-petraeae*, *Quercion pubescenti-petraeae*) and beech dominated forest types (*Cephalanthero-Fagion*) as well as species rich submontane and montane forest types (e.g. *Abieti-Fagion*) gain area under the assumptions of the authors whereas rather species poor high montane and subalpine forest types get superseded by the latter. Assuming both, increasing temperatures and precipitation the authors were not able to find significant changes in potential species richness (Kienast *et al.*, 1998). Comparable results have been found in a vast set of simulation studies of various authors (e.g. Kienast, 1991; Kienast *et al.*, 1998; Brzeziecki *et al.*, 1995; Kienast *et al.*, 1996; Theurillat *et al.*, 1998; Lexer, 2001 and Zebisch *et al.,* 2005). Nevertheless, broadleaved trees are not expected to expand their range throughout alpine stands.

Xerophytic forests in inner alpine dry valleys are extremely sensitive to changes in temperature and precipitation due to water limitation. If drought period length increases due to higher temperatures and moisture availability patterns change *Quercus pubescens* may be in advantage over *Pinus sylvestris* under very dry conditions due to physiological advantages. The lower drought tolerance and the long lived photosynthetic tissue of *Pinus sylvestris* might pose an advantage for *Quercus pubescens* (Weber *et al.*, 2007).

Increasing temperatures and decreasing water availability could also have effects on the competitivity among coniferous tree species. *Larix decidua* could become more competitive compared to *Pinus cembra* and *Picea abies* because of its ability to photosynthesize longer under drier conditions due to its stomatal conductance mechanisms (Anfodillo *et al.*, 1998; D'Arrigo *et al.*, 2004; Büntgen *et al.*, 2006). With respect to *Pinus cembra*'s reduced competitivity a simulation study by Bugmann *et al.* (2005) is confirming these trends, it finds *Pinus cembra* dominated forests situated on south facing slopes replaced by *Picea abies* dominated mixed forests.

In a large-scale simulation study by Lexer *et al.* (2002) substantial changes in natural species composition are found for temperature increases exceeding 1°C, favoring broadleaved over coniferous species. They conclude that under the analyzed set of climate change scenarios *Picea abies* will become unsuitable as a crop species in lower elevations.

In general changes in species competitivity and species composition could have a large impact on forest ecosystems and the goods and services provided. In a case study on two Swiss regions Schumacher and Bugmann (2006) conclude that vegetation shifts will have a stronger effect on biomass and species distribution than forest management.

Mortality

Changes in species competitivity and thus species composition as well as changes in mortality strongly affect the structure of forest stands. As stand structure is a very vital component of protective forests climate induced structural changes have the potential to veritably impact protective functions.

Increasing temperatures in combination with increasing drought stress are able to increase **abiotic mortality** in forest ecosystems. According to Dobbertin *et al.* (2005) increasing drought stress might fuel the decline of *Pinus sylvestris* in inner alpine dry valleys. This is underlined by a study by Rebetetz and Dobbertin (2004) where recently increasing mortality in *Pinus sylvestris* stands in Valais (Switzerland) is related to the strong climatic warming of the last decades.

Mortality caused by forest fires could gain importance in the European Alps under projected climate change. For the last decades of the 20th century (1971-2003) an increase in fire prone conditions, as a consequence of increasing dry periods, has been observed in Ticino (Switzerland). Especially the period from January to April, where forest fires have been historically most frequent, has become drier in the years from 1971 to 2003, indicating increasing fire risk due to climatic changes (Reinhard *et al.*, 2005). Schumacher and Bugmann (2006) and Fuhrer *et al.* (2006) are also emphasizing the increasing importance of forest fires in the European Alps under warmer and drier conditions. Schumacher and Bugmann (2006) conclude in a case study on two Swiss alpine regions that vegetation shifts will have a stronger effect on biomass and species distribution than forest management. The influences of changing wind disturbance patterns and harvesting activities are likely to be overridden by intensified fire regimes and directly climate influenced effects like growth changes (Schumacher and Bugmann, 2006).

Changes in storm frequency and magnitude are difficult to project with current climate models, however at least for the oceanic regions of Central Europe an increase in storm activity is possible (Zebisch *et al.*, 2005). An increase in storm frequency accompanied by increasing drought could accelerate changes in species composition due to the establishment of diverse regeneration niches (Fuhrer *et al.*, 2006).

Responses of mountain forests to climate change will be diverse and complex according to Lischke *et al.* (1998). Especially very uncertain features in regional climate change projections like windstorm and precipitation patterns might strongly affect mountainous forest ecosystems. In general the most climate sensitive regions are found in subalpine areas at the timberline ecotone and in areas which are already water limited like e.g. inner alpine valleys at the dry timber line (Bugmann, 1997; Lischke *et al.*, 1998).

Additional to abiotic effects on the structure and functioning of mountain forest ecosystems **biotic stressors** are seen as major players. Mountain forests are *inter alia* characterized by steep temperature gradients which make biotic disturbance regimes, particularly sensitive to climatic changes. Especially **poikilothermal insects**, being of major importance in alpine disturbance regimes, can be heavily influenced by changes in temperature and precipitation as well as with regard to some species by changes in wind storm regimes. In *Picea abies* dominated forests *Ips typographus* L. and *Pitiogenes chalcographus* L. are of particular importance in the disturbance regime (Christiansen and Bakke, 1988; Forster *et al.*, 1999; Jurc *et al.*, 2006). In the latency phase of the population cycle the beetles are using stressed trees for breeding (e.g. Christiansen and Bakke, 1988; Zemek *et al.*, 2003), whereas during an outbreak even vital trees may get attacked (Schröder and Lindelöw, 2002). Furthermore windstorm events are able to create large quantities of breeding material suitable for *Ips typographus* reproduction by uprooting or breaking trees and by weakening remaining trees by root ruptures favoring the development of bark beetle gradations (Göthlin and Schröder, 2000; Schröder, 2001; Wermelinger, 2004; Eriksson *et al.*, 2005). The observed increases in bark beetle calamities in the alpine region during the last two decades have been partly induced by severe windstorms (e.g., Viviane in 1990, Wiebke in 1992, Lothar in 1999) and furthermore favored by warmer conditions (Krehan and Steyrer, 2004; Engesser *et al.*, 2005). It is highly uncertain if and how altered wind storm patterns will change under climate change, but as it can be derived from the AFI more stands are becoming susceptible to wind throw due to the development of the age classes in Austrian forests (Anonymous, 2002a). Besides changes in wind regimes climate change will alter disturbance regimes in spruce dominated forests by enhancing multivoltinism of *Ips typographus* via rising temperatures (e.g. Volney and Fleming, 2000; Bale *et al.*, 2002; Baier *et al.*, 2007; Hlásny and Turcány, 2009) and by increasing drought stress (Christiansen and Bakke, 1988; Dutilleul *et al.*, 2000).

In general the spatial distribution of major insect herbivores is, in most of the cases, limited by climatic restraints rather than by host availability. This is of great importance for the development of the interactions between e.g. *Ips typographus* and its host as the current spatial distribution of *Picea abies* is strongly exceeding the thermal limits of *Ips typographus*. Warming could therefore trigger severe increases in bark beetle damages in higher elevation coniferous forests (Seidl *et al.*, 2009). Scenario based climate change impact assessments show strong increases in *Picea abies*' susceptibility to bark beetle infestations under climate change (Seidl *et al.*, 2006; 2008).

However not only the susceptibility to bark beetle attacks will be increased under climate change also the predisposition to defoliation by insects can be elevated under a changing climate as shown by recent outbreaks of *Cephalcia arvensis* Panzer in the Southern Alps. Increased temperatures during June and July during several years are seen as major factors leading to gradations, repeated defoliation and finally dieback of affected stands (Battisti, 2004).

Various bark beetle species are part of alpine *Pinus spp.* dominated ecosystems, most of them occurring secondarily on trees of reduced vitality. But, gradations may become more likely due to increasing dry spells and longer heat periods (Nierhaus-Wunderwald and Forster, 2000). Currently the pine stands of inner alpine dry valleys in Switzerland are prone to attacks of *Ips sexdentatus* Boern. and *Ips acuminatus*. Gyllenhal Increasing summer temperatures could favor the latter one by enabling the termination of a second generation increasing the probability of mass outbreaks. Furthermore rising temperatures could also promote higher population densities of other pine pests like *Tomicus piniperda* L. or *Tomicus minor* Hartig. In the Southern Alps an altitudinal range expansion of *Thaumetopoea pityocampa* Den. & Schiff. can be expected due to increasing temperatures (Battisti *et al.*, 2006).

Development of many poikilothermal organisms is positively influenced by higher temperatures but also negative effects are reported. An example for such a negative feedback is the collapsed outbreak cycle of the larch bud moth *Zeiraphera diniana* Gn. in the Upper Engadine Valley which can be mainly accounted to climate change (e.g. Battisti, 2004; Esper *et al.*, 2007). However, according to Esper *et al.* (2007) a breakdown of the bud moth epidemics could have strong impacts on the ecosystem by e.g. altering the nutrient cycle.

Besides impacts on pests also **fungal diseases** will be strongly affected by climatic changes. In mountainous regions the spatial and temporal distribution snow cover is a critical prerequisite for the development of several fungi. *Phacidium infestans* P. Karst. and *Herpotrichia juniperi* (Duby) Petrak are important diseases mainly affecting regeneration in subalpine environments, for the development of these fungi and the infection of new trees deep snow cover is needed (Nierhaus-Wunderwald, 1996). Also other fungi like the serious pine disease *Gremmeniella abietina* (Lagerberg) Morelet depends on snow cover. A long persisting snow cover in spring provides optimal moist conditions enabling a long development phase of the fungus. Tree mortality due to *Gremmeniella abietina* is particularly high after cold and wet summers providing good conditions for sporulation, spread and thus infection (Senn, 1999). Warm and dry summers, however, are lethal to the fungus (Nierhaus-Wunderwald, 1996). Increasing temperatures and decreasing precipitation thus might reduce canker and snow mould induced stress and mortality at high elevations in future, but the future development is hard to project due to major uncertainties in projecting local precipitation patterns and furthermore due to major uncertainties in predicting local snow depths and snow cover duration.

Some fungal diseases like *Diploida pinea* (Desm.) Kickx occurring on *Pinus nigra* Arnold, however, might be enhanced in their development when temperatures increase with a concomitant decrease of humidity (Maresi *et al.*, 2007). Regional increases of summer precipitation might favor the development of certain fungi, like *Dothistroma septosporum* which is affecting *Pinus spp.* (Kirisits and Cech, 2007).

Regeneration

In general climate change induced effects on forest regeneration are hardly researched in scientific literature. Targeted research on this topic is scare but as various simulation studies have been conducted it can be expected that changes in regenerational processes are implicitly considered. However some results have been encountered.

Increasing temperature accompanied by increasing drought and fire activity as well as enhanced senescence and mortality of mature individuals might lead to an increase in sites favorable to *Pinus sylvestris* regeneration as Hättenschwiler and Körner (1995) conclude on the basis of empirical observations. Comparable changes could be induced by an increase in storm frequency accompanied by increasing drought leading to an establishment of diverse regeneration niches (Fuhrer *et al.*, 2006).

A major climate change effect on regeneration might be encountered at the upper tree line, but the climate change sensitivity of the upper tree line will be topic of the following paragraphs.

Tree line

As according to Bugmann (1997) the alpine (cold) timberline is one of the most climate sensitive ecotones, strong climatic effects can be expected in these regions. Especially the vertical distribution of the tree line has been a subject to several studies. The availability of suitable microsites is a crucial prerequisite for a vertical increase of the tree line. In absence of such microsites tree invasion into alpine regions might show substantial time lags even under strongly relaxed climatic conditions (Bolli *et al.*, 2007).

Nicolussi *et al.* (2005) conducted an empirical observation study focusing on the *Pinus cembra* dominated tree line in the Kauner Valley in Tyrol. During the observation period from the first half of the 19th century to current conditions the tree line rose from 2180 m a.s.l. to 2245 m a.s.l. additionally *Pinus cembra* saplings have been recorded up to an elevation of 2370 m a.s.l. pointing at a progressing process (Nicolussi *et al.*, 2005).

But besides climatic changes land use changes are also heavily influencing the tree line as shown by Gehrig-Fasel *et al.* (2007) who conclude in a study for Switzerland that abandonment of agriculturally used areas is a major driver for the establishment of new forest patches at the tree line ecotone. According to their results only 4% of the observed upward shifts can be directly linked to a warming climate, but this fraction is likely to increase under a continuingly warmer conditions and when observation periods are elongated (Gehrig-Fasel *et al.*, 2007). Similar results have been reported for Swiss *Pinus cembra* tree lines. A continuing upward movement of the tree line ecotone can be expected particularly in regions where the current is below the potential tree line due to land use practices such as e.g. high pastures (Vittoz *et al.*, 2008).

For climate change impacts on tree lines in the Calcareous Alps some simulation studies have been conducted in Austria. *Pinus mugo* Turra might be able to expand its altitudinal range quite rapidly if climate warming relaxes the environmental constraints at high elevations (Dullinger *et al.*, 2003). In a simulation case study on climate change induced tree line shifts on Mt. Hochschwab in Styria Dullinger *et al.* (2004) expect *Pinus mugo* land cover to rise from currently 10% up to 24% to 59% of the study area within the simulation period of 1000 years. These results are corresponding wit the results of a large scale modeling study for the north-eastern Calcareous Alps (Dirnböck *et al.*, 2003).

Swiss simulation studies like Bugmann *et al.* (2005) show strong rises of the tree line up to 2500 m a.s.l. accompanied by upward shifts of the associated forest types. Theurillat *et al.* (1998) conclude on upward shifts of about 100 to 200 m a.s.l. for an annual mean temperature increase of 1-2°C. For stronger warming of about 3 to 4°C the kampfzone would likely rise in the current alpine belt accompanied by a shift of the timber line into the low alpine belt (Theurillat *et al.*, 1998).

The assumptions regarding the climatic drivers used to conduct these simulation studies have been low compared to current projections, especially the values used by Dullinger *et al.* (2004) (temperature increase of 0,65 to 2°C until 2150) are far below current assumptions. Therefore the climate sensitivity of the tree line might be even underestimated in literature.

4.1.1.2 Natural hazards

Flooding

The frequency and magnitude of flood events is strongly influenced by changing precipitation patterns and temperature. Rising temperatures will reduce snow cover duration and snow depth resulting in significant effects on runoff and water availability (Beniston, 2003). Additionally shrinking glaciers will contribute to these changes. Discharge of torrents and mountain rivers in glaciated watersheds is currently balanced by glaciers during summer heat waves lacking precipitation. Due to the loss of their volume under climate change the glaciers will be unable to maintain torrent and river discharge via increased ablation rates during dry spells. Therefore a greater variability in discharge can be expected influencing flood occurrence (Zappa and Kan, 2007).

According to Graham (2005 in Beniston, 2005) flood risk might tend to increase in late winter at the end of the century in the Alps, due to more abundant precipitation in the winter half year. Additionally coincidence of increasing torrential rain events with snow melt periods could significantly increase the frequency and magnitude of flood events (Beniston, 2005).

Debris flow

Climate induced changes in debris flow activity have been subject to scientific research especially in high altitudes, however at lower elevations where forests are able to influence debris flow processes research is sparse. As debris flows are mainly triggered by abundant rain, snow-melt and runoff separately or in combination changing precipitation patterns will strongly affect debris flow frequency and magnitude. For Switzerland an increase of rain events able to trigger debris flows has been observed throughout the 20th century (Rebetetz *et al.*, 1997). Simultaneously glacial and permafrost retreat reveal large amounts of easily erodible, unstable debris masses due to continuing warming (Zimmermann and Haeberli, 1992; Haeberli and Beniston, 1998; Watson and Haeberli, 2004). This will, as indicated by a study from the Italian Alps, result in an increasing debris flow frequency at the margins of glaciers (Chiarle *et al.*, 2007).

Landslide

According to Beniston (2005) melting permafrost and changes in hydrology will change the pedological conditions and thus the stability of slopes might be decreased resulting in potentially increased frequency and magnitude of landslides. But as changes in precipitation patterns will vary strongly throughout the Alps the spatial pattern of landslide sensitivity to climate change will be complex. This complexity is amplified by the fact that landslide activity is sensitive to short term (daily to weekly) as well as long term (monthly to even yearly) changes in precipitation (Asch, 1996; Buma and Dehn, 1998; Buma and Dehn, 2000).

More detailed information on landslide sensitivity to climatic changes is presented by first studies using computer models. A case study by Dehn (1999) for a mudslide in the Italian Dolomites (1320 – 1520m a.s.l.) has been conducted as a simulation study. Under his assumptions the author concludes on a decreasing landslide activity in spring for the period from 2070 to 2099 triggered by increased winter temperatures. Higher temperatures in winter will reduce the storage of precipitation in the snow pack resulting in a lower availability of melt water in spring and therefore lower runoff peaks which decrease landslide activity. For this case study the decrease in landslide activity in spring is considered to be of high confidence, whereas for the other seasons no clear trend could be found (Dehn, 1999).

Rock fall

Some rock fall sensitivity studies have been conducted evaluating observed climate change but literature on the effects of the projected climatic changes on rock fall activity is sparse. Similarly to debris flow sensitivity research significantly more research efforts have been dedicated to the periglacial regions.

An overview is presented by Gruner (2004) evaluating 800 rock fall events in the northern Swiss Alps. For the period from 1500 to 1900 no correlation has been discernible between warm and humid phases and increased rock fall activity. For the relatively cold period from 1950-1980 an increase of rock fall events in winter is reported due to rock mass contraction and joint expansion. In this period the rock fall activity was higher compared to the periods from 1900 to 1950 and since 1980. This is quite surprising as in the last decades of the 20th century extreme precipitation events tended to increase. The author concludes that a general increase of rock fall activity due to warmer conditions is not discernible and within the next 50 years rock fall activity is unlikely to increase, whereas seasonality might change a little. Due to warming conditions rock fall events in winter might decrease further whilst a moderate increase could be expected during the summer half year due to increasing extreme precipitation events (Gruner, 2004).

Avalanche

Snow cover, terrain and weather are heavily influencing avalanche activity therefore according to Föhn (1992) the relationship between climate and avalanche activity is less direct than between climate and snow cover. For the second half of the last century no trends towards increases or decreases in avalanche activity could be observed by using data of 84 Swiss avalanche observation stations. This is in contrast to the fact that winter precipitation increased significantly during the observed period (Laternser and Schneebeli, 2002).

In lower altitudes projected climate change is likely to lead to reduced snow loads due to rain replacing snowfall, however at higher altitudes snow loads might increase due to more abundant solid precipitation. With respect to the snow line a rise of 100 to 150 m is expected for each increasing °C in winter mean temperature (Watson and Haeberli, 2004).

An early simulation study by Glazovskaya (1998) on avalanche season length and avalanche activity uses a very crude and large scale approach covering the northern hemisphere. The author expects a shorter avalanche season in the Alps due to a calculated decrease (up to -50%) in heavy snowfall events (Glazovskaya, 1998). However, because of the large scale approach these results have to be seen as tentative ones showing only a possible trend of future development. Another more detailed simulation study has been conducted by Martin *et al.* (2001) investigating avalanche hazard development in the French Alps for the 21st century. According to their results avalanche hazard might decrease slightly from November to January and more pronounced in February and May to June due to a shortening snow cover duration. Furthermore it is expected that the importance of loose snow avalanches decreases (Martin *et al.*, 2001).

The complexity of rising snow lines, changing precipitation patterns and wind regimes in combination with the complex topography of the Alps is impeding a conclusive general statement on climate change sensitivity of avalanche activity. Climate change effects will vary strongly on a local to regional scales lacking area-wide scientific investigation by now.

4.1.2 Impacts on protective functions

Protective forests require specific structural and compositional properties to maintain the protective function against regarding natural hazards. These forest properties (e.g., species composition, diameter distribution, N/ha, maximum gap size) are defined by the occurring hazard(s) against the forest has to protect (Frehner *et al.*, 2005). As shown by the last chapter on sensitivities the forest ecosystems as well as the hazardous processes are potentially sensitive to climatic changes. Due to this complexity climate change impacts are difficult to assess. Additionally considerable time lags between the reactions of the forest ecosystem and the reactions of the hazardous processes can occur. Such time lags and system inertia have to be addressed as a considerable element of uncertainty.

At large it has to be stated that targeted research on climate change impacts on the vital forest service protection against natural hazards is scarce. For regions above the timberline substantial research has been conducted assessing glacier and permafrost related hazards like glacial lake outbursts, debris flows, rock slides and falls, moraine dam failures and ice avalanches. These events often characterized by enormous involved energies and low frequencies and are thus of minor interest for this thesis as forests can hardly influence these processes.

4.1.2.1 Flooding

An increasing frequency of torrential rain events will affect erosion rates, runoff, discharge, and sedimentation rates in alpine catchments and are potentially damaging to hydropower facilities. Moreover sediment deposition on agricultural lands due to flooding will lead to reduced productivity besides the direct damages on crops (Beniston, 2005).

Increasing forest cover in subalpine and alpine regions due to tree line shifts is enhancing flood protection in general due to runoff dampening. These effects of forest cover can be quite effective in small catchments but are limited on larger scales as shown by Bendix (1997) in a large scale study on human impact on flood discharge in the river Rhine catchment. His results based on a GIS-based water-balance model show that converting 25% of the farmland within the catchment to coniferous forests would only result in a water level reduction of 6 cm at the Cologne gauging station during a flood event comparable to the 1993 event (Bendix, 1997).

Generally spoken, the smaller the catchment the larger are the possibilities to enhance flood protection by natural or artificial reforestation. But, in smaller catchments the impact of large scale disturbances like wind throw or fire on flood protection can also be expected to be more pronounced. Summarizing, flood protection by forests is particularly important in headwater catchments sheltering smaller settlements and infrastructure.

4.1.2.2 Debris flow

Debris flows starting in the current periglacial region are often characterized by large magnitudes and therefore the protective effect of forests is limited. For debris flows triggered below the timber line forests can affect frequency and magnitude of events positively. Forest cover is able to cover and stabilize erodible debris, dampen water infiltration into the soil, alter percolation patterns and reduce soil moisture. These effects are most likely to enhance protection in the starting zone, in the transit and run out zone forest influence is less distinct. Concerning channeled flows woody debris can even increase the hazard by clogging the channel and potentially releasing accumulated debris leading to higher magnitudes.

Climate induced increases in forest cover above all by tree line shifts might therefore increase the protection. However due to the rather slow pace of such tree line shifts, uncertainties in the future development of disturbance patterns and projected increases of torrential rain fall events large uncertainties remain.

4.1.2.3 Landslide

Similar to debris flow protection, forest protection against landslides is most efficient in the starting zone. Forests are able to dampen runoff and water infiltration and thus lower the soil water table and soil can be stabilized by rooting. Hence maintenance of vegetation and *inter alia* forest cover is essential (Beniston, 2003). In the transit and run out zone forest cover and vegetation effects are of minor importance. A climate induced tree line rise as projected by several authors may enhance the protective function at least against shallow land slides where rooting in the upper soil layers is a crucial stabilizing factor. Regarding uncertainties a similar reasoning can be conducted like for debris flow protection. Especially due to the fact that only one case study by Dehn (1999) is concentrating on the climate change sensitivity of landslides a clear statement on the development of the protective function against landslides is virtually impossible.

4.1.2.4 Rock fall

Protective forests sheltering human buildings and infrastructure against rock fall should feature spatially and temporally continuous forest cover with certain structural specifications throughout the rock fall trajectory. Nevertheless the protective function can be utilized most efficiently in the starting zone by preventing detachment of rocks from bedrock or by stopping rocks before they gain speed and thus energy. Along the trajectory in the transit and run out zone high stand densities and/ or trees of a certain diameter are beneficial to reduce the energy of rolling and jumping rocks. At stand level disturbances like wind throw, fire or bark beetle infestations will have significant negative impacts on protection against rock fall by considerably altering stand structure (Schumacher and Bugmann, 2006; Woltjer *et al.*, 2008). Statements on the future development of the protective function against rock fall are hard to draw as prospective research is very scarce, however changing disturbance regimes will have a strong impact.

4.1.2.5 Avalanche

With respect to the protective function against avalanches a rising tree line will reduce possible starting zones. However serious time lags can be expected for this rise indicating uncertainties.

As for the other hazards the disturbance regimen will play a major role in determining whether the protective function might be enhanced or reduced under climate change. A loss of snow pack stabilizing trees due to disturbances is very unfavorable for avalanche protection as these structural elements do not only impede avalanche formation but also reduce snow gliding. Snow gliding can be a major restraint for regeneration on steep slopes posing a serious threat to the maintenance of over aged protective forests.

Unfortunately little information is available on climate change sensitivity of avalanche activity and the interaction with forest structure and functioning. Important issues like the development of different avalanche types under climate change are hardly addressed at all in scientific literature. Nevertheless information regarding this topic would be extremely beneficial in assessing potential climate change impacts on the protective function of mountain forests.

By and large it can be said that currently climate change impacts on the protective function of mountain forests against natural hazards is not thoroughly understood. During this review substantial knowledge gaps have been encountered pointing at clear research needs.

4.2 Case studies

4.2.1 Region A Oberes Murtal

4.2.1.1 Sensitivity

The sensitivity assessment consists of two major parts, the assessment of forest ecosystem sensitivities and the assessment of natural hazard sensitivities.

Forest ecosystem

The sensitivity assessment is conducted in two steps, first the current state is assessed and thereafter the forest response is judged for each indicator at assessment unit level (cf. chapter 2.4.2.1).

First of all the current **state** of the forest ecosystem is assessed for the Upper Mur Valley according to the classification presented in table 2.

Growth

Picea abies: Due to the high annual increment of Norway spruce according to the AFI (Anonymous, 1997) a good state (class 1) of the indicator growth is expected at all elevations.

Larix decidua: According to the high annual increment of European larch as reported by the AFI (Anonymous, 1997) a good state (class 1) of the indicator growth is expected at all elevations.

Other coniferous species: As currently other coniferous species are just occurring at elevations > 1200m in the data of the AFI the current state is only judged for this elevation belt. Due to the low annual increment the state is currently estimated to be poor (class 3) (Anonymous, 1997).

Broadleaved species: Due to the currently low annual increment the state of the indicator is judged to be poor (class 3) too (Anonymous, 1997).

Mortality

Due to the low level of detail with respect to the data of the HEM the current state of mortality is judged to be average (class 2) for all tree species and assessment units (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Regeneration

Picea abies: Currently regeneration of Norway spruce is expected to be possible at almost all sites thus the current is estimated to be good (class 1).

Larix decidua: cf. *Picea abies*

Other coniferous species: As this category is consisting of predominantly *Pinus cembra* in regions higher than 1200m the current state is estimated to be average (class 2) because of snow dependant fungi (cf. e.g. Nierhaus-Wunderwald, 1996).

Broadleaved species: Due to the current climatic conditions the current state of the indicator regeneration is expected to decrease along the altitudinal gradient (class 1 to 3 with increasing elevation).

Tree line

Due to current and abandoned land use practices the actual tree line differs strongly to the potential tree line in some regions of the case study. Therefore an average (class 2) state is assumed for all species as according to the classification all of them are occurring at tree line altitudes.

In the next step the **response** of the indicators to climate change is assessed for each tree species at assessment unit level. This is done for both assessment time steps at once.

Growth

In table 39 the response classes used for the assessment are described (cf. table 3) and examples are presented for the indicator growth.

Table 39: Response classes for the indicator growth and examples.

Class	Description	Example
1	Positive response	Positive response of the indicator growth to the climate change exposure (e.g. increasing growth rates at high altitudes due to increasing temperatures)
2	Hardly any positive or negative response	Hardly any response due to climate change exposure is expected, or responses are not predictable
3	Slight negative response	Small negative response of the indicator growth expected, e.g. growth reduction due to dry spells
4	Moderate negative response	Moderate response of the indicator growth expected, e.g. growth reduction due to climatic exposure close to tree species niche boundary
5	Strong negative response	Strong negative response of the indicator growth due to e.g. exposure exceeding the physiological borders of a regarded species

Picea abies: Growth is expected to increase (class 1) for the first assessment period (2021 – 2050) at all altitudinal stages due to an increase in temperature and precipitation during the summer months. This assessment has been made according to e.g. Hasenauer *et al.* (1999). For the second time period (2071 – 2100) it is expected that growth at low elevations will show a slight decrease (class 3) due to warmer summer temperatures accompanied by a minor precipitation decrease resulting in increasing drought stress. In middle elevations growth is expected to hardly show any response at all (2), whereas in high elevations growth is judged to be responding positively (class1) *inter alia* due to the relaxation of the harsh environment in subalpine regions (e.g. Paulsen *et al.*, 2000).

Larix decidua: In general similar reasoning can be conducted for European larch like for Norway spruce, especially for the first assessment period where temperature and precipitation are projected to increase (response class 1 for all elevations). For the second period the judgments are somewhat alleviated because of physiologic advantages of larch (D'Arrigo *et al.*, 2004; Wilmking *et al.*, 2004). Therefore growth is not expected to change at low elevations (class 2) whereas in middle to high altitudes a slight increase is expected (class 1).

Other coniferous species: Here a similar reasoning is applied like for larch as the most important species in the Upper Mur Valley in this category is *Pinus cembra*.

Broadleaved species: For broadleaved species growth is expected to be increasing (class 1) at all elevations during both time slices because of longer growing seasons and thus more favorable growing conditions accompanied by increasing competitivity of broadleaved species (e.g. Theurillat *et al.*, 1998).

Abiotic mortality

In table 40 the response classes used for the assessment with regard to abiotic mortality are presented and short examples are given.

Table 40: Response classes for the abiotic mortality and examples.

Class	Description	Example
1	Positive response	Positive response of the indicator due to the expected climate change exposure (e.g. decreasing abiotic morality at high elevations due to a relaxation of the harsh climatic environment)
2	Hardly any positive or negative response	Hardly any response due to climate change exposure is expected, or responses are not predictable
3	Slight negative response	Small negative response of the indicator expected, e.g. due to a small increase in dry spells (small decrease in summer precipitation) leading to higher mortality rates
4	Moderate negative response	Moderate negative response of the indicator expected, e.g. due to an increase in dry spells (decrease in summer precipitation) causing higher mortality rates
5	Strong negative response	Strong negative response of the indicator expected, e.g. due to an increase in dry spells (strong decrease in summer precipitation e.g. >-20%) causing higher mortality rates

Picea abies: With regard to abiotic mortality the response of Norway spruce under the considered exposure is expected to be low. As no strong changes in water availability and storm and fire activity can be projected the response is generally judged as negligible (class 2). However for the growth phases youth and pole stage a positive response (class 1) is expected at higher elevations due to shorter snow cover and therefore less mechanic damage due to snow gliding and creeping.

Larix decidua: cf. *P. abies*

Other coniferous species: cf. *P. abies*

Broadleaved species: Generally the response is seen to be positive (class 1) due to a relaxation of the environment for broadleaved species at middle and higher elevations resulting in decreasing abiotic mortality. At lower elevations and in the second assessment period as well as for middle elevations no major changes in abiotic mortality are expected (class 2).

Biotic mortality

In table 41 the response classes used for the response of biotic mortality are presented and short examples are given.

Table 41: Response classes for biotic mortality and examples.

Class	Description	Example
1	Positive response	Positive response of the indicator expected, e.g. due to shorter snow cover resulting in decreasing snow fungi related mortality
2	Hardly any positive or negative response	Hardly any response due to climate change exposure is expected, or responses are not predictable
3	Slight negative response	Small negative response due to e.g. exposure supporting higher survival rates for biotic pests during winter season (e.g. small temperature increase)
4	Moderate negative response	Moderate negative response due to e.g. exposure reaching favorable conditions for pest development
5	Strong negative response	Strong negative response due to e.g. increasingly favorable climatic conditions supporting bark beetle multivoltinism and thus mass gradations

Picea abies: In general, warmer climatic conditions are able to enhance development of poikilothermal insects. Therefore pole and timber stand stages of spruce are seen to be responding negatively (class 3 to 5) due to increasing pressure by first and foremost bark beetles (e.g. Seidl *et al.* 2009) especially in the lower altitudes and during the second assessment period. In the second period even at high elevations negative responses, primarily caused by bark beetles, are expected. For youth stages at high elevations the indicator is seen to be responding positively (class 1) due to possibly shorter snow cover durations reducing mortality caused by snow dependent fungi like for example *Herpotrichia juniperi*.

Larix decidua: In general only minor responses (class 2) have been assumed for European larch with regard to biotic mortality. Only for the pole and timber stages in the middle and lower altitudes slightly increasing pest induced mortality has been assumed (class 3) in the second assessment period due to possibly increasing damages by e.g. *Ips acuminatus* (Battisti, 2004).

Other coniferous species: Slightly increasing mortality (class 3) due to bark beetles is expected at lower and middle elevations due to warmer temperatures (Nierhaus-Wunderwald and Forster, 2000; Battisti, 2004). For the higher regions and the youth stages a slightly positive (class 1) trend was assumed due to a possible decreasing importance of snow dependent fungal diseases like snow moulds and *Gremmeniella abietina*, especially important for *Pinus cembra* (Nierhaus-Wunderwald, 1996).

Broadleaved: No responses (2) have been assumed due to a lack of information.

Regeneration

In the following table 42 the response classes used for the assessment of regeneration responses are presented and short examples are given.

Table 42: Response classes for regeneration and examples.

Class	Description	Example
1	Positive response	Positive response of the indicator expected e.g. exposure positively influencing regeneration conditions at high elevations due to increasing temperatures
2	Hardly any positive or negative response	Hardly any response due to climatic exposure is expected, or responses are not predictable
3	Slight negative response	Small negative response of the indicator due to e.g. a small degradation of regeneration conditions
4	Moderate negative response	Moderate negative response of the indicator due to e.g. a moderate degradation of regeneration conditions
5	Strong negative response	Strong negative response of the indicator due to e.g. a strong degradation of regeneration conditions

For all coniferous species a positive response with regard to regeneration in suitable sites (class 1) has been expected for the higher regions due to less harsh conditions and longer growing seasons. For the broadleaved species conditions are seen to improve (class 1) at middle and high elevation stages. In other altitudinal stages hardly any response (class 2) can be projected.

Tree line

In the following table 43 the response classes for the assessment of tree line responses are presented and short examples are given.

Table 43: Response classes for the tree line and examples.

Class	Description	Example
1	Positive response	Positive response of the indicator expected e.g. due to an increase in favorable conditions (combined effects growth, mortality, regeneration) for a tree line upward shift
2	Hardly any positive or negative response	Hardly any response due to climatic exposure is expected, or responses are not predictable
3	Slight negative response	Slight negative response of the indicator due to e.g. severe precipitation decreases in the summer period
4	Moderate negative response	
5	Strong negative response	

For all species a positive response (class 1) of the tree line has been assumed for the second assessment period, for the first assessment period only minor responses (class 2) have been assumed due to system immanent inertia (e.g. Bolli *et al.*, 2007).

As current state and forest response have been assessed the estimates aggregated to sensitivity classes according to figure 5. The full table including the results for each assessment unit on the three-part scale for the Upper Mur Valley can be seen in appendix E - Forest sensitivity assessment tables (Table A 1, Table A 2, Table A 3, Table A 4 and Table A 5). These classes at the assessment unit level are converted into cardinal values between zero and one according to AHP preference values presented in table 5 (cf. also figure 6).

The preference values are now weighted with their area share for each assessment unit to calculate a weighted mean value for each indicator. In table 44 these weighted mean values, for the sensitivity of the single indicators, are shown for the Upper Mur Valley case study.

Table 44: Cardinal sensitivity values at the indicator level for the Upper Mur Valley generated by building weighted mean values according to the area shares of the assessment units (values smaller than 0,63 represent negligible negative or even positive sensitivities, values between 0,63 and 0,89 represent slight to moderate negative sensitivities and values larger than 0,89 are representing strong negative sensitivities).

Indicator	Weighted mean AHP preference value 2035	Weighted mean AHP preference value 2085
Growth	0,32	0,32
Abiotic mortality	0,32	0,32
Biotic mortality	0,53	0,71
Regeneration	0,32	0,32
Tree line	0,32	0,32

As a next step towards the estimation of the potential impact and thus vulnerability the preference values of the indicators are weighted according to their relevance for the protection against a certain natural hazard (table 6). This results in protective function specific cardinal sensitivity estimates (table 45). At the end of this sensitivity appraisal procedure these cardinal forest sensitivity estimates are converted into ordinal values on a three-part scale according to table 7. In table 45 the results of this conversion, the protective function specific sensitivity classes for the Upper Mur Valley are displayed.

Table 45: Results of the forest sensitivity assessment, cardinal sensitivity estimations and their conversion into classes according to table 7 (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

Protective function	Cardinal sensitivity estimate		Sensitivity class	
	2035	2085	2035	2085
Flooding	0,38	0,43	**1**	**1**
Debris flow	0,39	0,44	**1**	**1**
Landslide	0,38	0,44	**1**	**1**
Rock fall	0,37	0,42	**1**	**1**
Avalanche	0,38	0,43	**1**	**1**

Natural hazards

The second part of the sensitivity assessment is to assess the sensitivities of the regarded natural hazards. Similar to the assessment of the forest ecosystem sensitivities the current state and the response of the indicators are assessed.

The estimates about the current **state** of the natural hazards have been obtained by interviewing the regional manager of the respective case study. For each hazardous process the two indicators frequency and magnitude have been examined and judgments have been done on tripartite scales (cf. table 8 and table 9).

The hazard specific state estimates can be seen in table 18 according to the interview with the regional manager of the management district Oberes Murtal

For the assessment of the natural hazard **response** to climate change the estimates of the regional managers (cf. table 19) are taken into account, but evidence from the literature review are also considered. The classes which are used for the assessment of frequency and magnitude responses are displayed in table 46 and table 47 and a short description of the classes is provided.

Table 46: Classes used to appraise response to climate change exposure with regard to the indicator frequency.

Class	Description	Example
1	Positive response	Positive response of the indicator is expected, frequency is expected to decrease
2	Hardly any positive or negative response	Hardly any response due to climatic exposure is expected, or responses are not predictable
3	Slight negative response	Small negative response of the indicator, frequency is expected to increase slightly
4	Moderate negative response	Moderate negative response of the indicator, frequency is expected to increase moderately
5	Strong negative response	Strong negative response of the indicator, frequency is expected to increase strongly

Table 47: Classes used to assess response to climate change exposure with regard to the indicator magnitude.

Class	Description	Example
1	Positive response	Positive response of the indicator is expected, magnitude is expected to decrease
2	Hardly any positive or negative response	Hardly any response due to climatic exposure is expected, or responses are not predictable
3	Slight negative response	Small negative response of the indicator, magnitude is expected to increase slightly
4	Moderate negative response	Moderate negative response of the indicator, magnitude is expected to increase moderately
5	Strong negative response	Strong negative response of the indicator, magnitude is expected to increase strongly

Flooding

Frequency: The frequency of floods is expected to increase slightly (class 3) for the fist assessment period due to possibly more abundant precipitation and more frequent torrential rain events. For the second period a moderate increase in frequency (class 4) is expected due to a further increase in torrential rain events.

Magnitude: With regard to magnitude a similar reasoning like for the indicator frequency is applied (class 3 and 4).

Debris flow

A similar reasoning like for flooding is applied, as these processes are often interlinked and triggered by similar conditions.

Landslide

Frequency: For the first assessment period a slightly negative development (class 3) is expected due to increasing summer and winter precipitation. For the second period only minor responses (class 2) are assumed as only winter precipitation tends to increase, accompanied by increasing temperatures reducing water storage in the snow pack (cf. Dehn, 1999).

Magnitude: Hardly any response (class 2) with regard to landslide magnitude is expected for both time horizons.

Rock fall

Frequency: For the first period hardly any response (class 2) is expected due to warming conditions reducing joint expansion. For the second period a slight increase in rock fall frequency (class 3) is assumed due to the possibility of more frequent and severe torrential rain events (cf. Gruner, 2004).

Magnitude: For magnitude a similar reasoning is applied like for the indicator frequency (class 2 and 3).

Avalanche

Frequency: Hardly any response (class 2) is expected with regard to frequency.

Magnitude: For the first period only negligible responses (class 2) are assumed and for the second period a moderate increase in avalanche magnitude (class 4) is expected due to more winter precipitation.

For each hazardous process and indicator the state and response estimates are aggregated according to figure 5, resulting in two sensitivity estimates (time horizons

2035 and 2085) for each indicator per natural hazard. The aggregation of the sensitivity estimates for frequency and magnitude is done according to the matrix presented in figure 9. The results of this procedure for the case study region Upper Mur Valley are presented in table 48, displaying the sensitivity for all five natural hazards and for the two assessment time steps.

Table 48: Results of the hazard specific sensitivity assessment (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

Natural hazard	Sensitivity class 2021 - 2050	Sensitivity class 2071 - 2100
Flooding	3	3
Debris flow	3	3
Landslide	1	1
Rock fall	1	2
Avalanche	1	2

4.2.1.2 Potential impacts

To obtain a potential impact estimate for a certain protective function the sensitivities of the forest ecosystem and the natural hazards assessed during the last chapter have to be combined according to the matrix presented in figure 10. The results of this aggregation, the potential impacts, are depicted in table 49 broken down into protective function and time horizon.

Table 49: Potential impacts for the Upper Mur Valley, the result of the aggregation of forest and natural hazard sensitivities (1 = hardly any or small negative potential impacts, 2 = medium negative potential impacts and 3 = strong negative potential impacts).

Protective function against	Potential impact 2021 - 2050	Potential impact 2071 - 2100
Flooding	2	2
Debris flow	2	2
Landslide	1	1
Rock fall	1	2
Avalanche	1	2

4.2.1.3 Adaptive capacity

The adaptive capacity of the case study region Oberes Murtal is medium (class 2) according to the AHP calculation. The preference values for the single indicators and the aggregated preference values as well as the discretized adaptive capacity class can be seen in table 50.

Table 50: Preference values for the single indicators (small values indicate small adaptive capacities and higher values are indicating higher adaptive capacities), weighted preference value as well as the discretized adaptive capacity (class 2 = medium adaptive capacity).

Indicator	Preference value
Road network density	0,845
Share of forest owners <200ha	0,367
Degree of organization and information of small scale owners	0,500
Academic staff BFI	0,145
BFI foresters	0,379
Academic staff WLV	0,155
Office staff WLV	0,309
Production staff WLV	0,159
Budget WLV	0,196
Weighted preference values	0,336
Adaptive capacity class	**2**

4.2.1.4 Vulnerability

After the aggregation of potential impacts and the adaptive capacity according to the vulnerability matrix (figure 13) the final results can be presented (table 51). For the first assessment period the majority of protective functions show a low vulnerability however for the protection against flooding and debris flow the vulnerability is medium. With regard to the second assessment period the vulnerability of the protection against flooding, debris flow and landslide remains on the same level like for the first time horizon. For the protection against rock fall and avalanches the situation is deteriorating as the vulnerability changes from low to a medium level.

Table 51: Results of the vulnerability assessment for the Upper Mur Valley (class 1 = low, class 2 = medium (2) and class 3 = high vulnerability).

Protective function against	Vulnerability 2021 - 2050	Vulnerability 2071 - 2100
Flooding	2	2
Debris flow	2	2
Landslide	1	1
Rock fall	1	2
Avalanche	1	2

4.2.2 Region B Oberes Inntal

4.2.2.1 Sensitivity

Forest ecosystem

The sensitivity assessment is conducted in two steps, first the current state is assessed and thereafter the forest response is judged for each indicator at assessment unit level (cf. chapter 2.4.2.1).

First the current **state** of the forest ecosystem is assessed for the Upper Inn Valley according to the classification presented in table 2.

Growth

Picea abies: Due to the intermediate annual increment of Norway spruce according to the AFI (Anonymous, 1997) an average state (class 2) of the indicator growth is expected at all elevations.

Larix decidua: According to the intermediate annual increment of European larch as reported by the AFI (Anonymous, 1997) an average state (class 2) of the indicator growth is expected at all elevations.

Pinus sylvestris: According to the low annual increment of Scots pine as reported by the AFI (Anonymous, 1997) a poor state (class 3) of the indicator growth is expected at all elevations.

Other coniferous species: As currently other coniferous species are just occurring at elevations > 1200m in the data of the AFI the current state is only judged for this elevation belt. Due to the low annual increment the state is currently estimated to be poor (class 3) (Anonymous, 1997).

Broadleaved species: Due to the currently intermediate annual increment the state of the indicator is judged to be average (class 2) (Anonymous, 1997).

Mortality

Due to the low level of detail with respect to the data of the HEM the current state of mortality is judged to be average (class 2) for all tree species and assessment units (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Regeneration

Picea abies: Currently regeneration of Norway spruce is expected to be possible at almost all sites above 900m thus the current state for these regions is estimated to be good (class 1). With respect to the sites lower than 900m an average state (class 2) is assumed due to relatively dry conditions.

Larix decidua: cf. *Picea abies*

Pinus sylvestris: Regeneration of Scots pine is expected to be possible at almost all suitable sites and thus the current state is estimated to be good (class 1) at all elevations.

Other coniferous species: As this category is consisting of predominantly *Pinus cembra* in regions higher than 1200m the current state is estimated to be average (class 2) because of snow dependant fungi (cf. e.g. Nierhaus-Wunderwald, 1996).

Broadleaved species: Due to the current climatic conditions the current state of the indicator regeneration is expected to decrease along the altitudinal gradient (class 1 to 3 with increasing elevation).

Tree line

Due to current and abandoned land use practices the actual tree line differs strongly to the potential tree line in some regions of the case study. Therefore an average (class 2) state is assumed for all species occurring at tree line altitudes. The current state of *Pinus sylvestris* is assumed to be good (class 1) as it is not occurring at tree line altitudes and thus no difference between actual and potential tree line is found.

During the appraisal of forest responses the **response** of each indicator is assessed at assessment unit level for the two time horizons. The reasoning applied is presented in the following paragraphs.

Growth

Picea abies: For the first period growth is expected to increase (class 1) at high elevations due to warmer temperatures, whereas in middle and low elevations hardly any change (class 2) in growth is expected due to not changing summer precipitation. For the second period a strong decrease in annual increment (class 5) is expected for the lower regions due to severe decreases in summer precipitation. In middle elevations growth is expected to decrease slightly (class 3) and at high altitudes changes are judged to be only minor (class 2).

Larix decidua: In general similar reasoning can be conducted for European larch like for Norway spruce, especially for the first assessment period where summer precipitation is not changing. For the second period the judgments are somewhat alleviated because of physiologic advantages of larch (D'Arrigo *et al.*, 2004; Wilmking *et al.*, 2004). Therefore growth is expected to be moderately decreasing at low elevations (class 4) whereas in middle elevations a small decrease (class 3) is expected. At higher elevations the responses to climate change exposure are seen to be negligible (2).

Pinus sylvestris: A similar reasoning like for *Picea abies* is applied for Scots pine due to strong Viscum album infestations at middle and especially at low elevations which are increasing the water demand of Scots pine and thus eliminating the physiological advantages.

Other coniferous species: This category mainly consists of *Pinus cembra* at high elevations where for the first period a slightly positive growth trend is expected (class 1) and for the second period only negligible responses are expected (class 2) in a currently mostly not water limited high altitude ecosystem probably facing increasing drought stress under projected conditions.

Broadleaved: At low elevations hardly any change (class 2) is expected for both assessment periods due to increasingly dry conditions during the summer period. For the first period at middle and high elevations a positive growth trend (class 1) is assumed due to higher temperatures. For the second period growth is expected to be slightly declining (class 3) at low and middle elevations and a slight increase is expected (class 1) at high elevations.

Abiotic mortality

Picea abies: For the first assessment period the responses are expected to be of little magnitude. In higher elevations in youth and pole stages the responses might be positive (class 1) due to less snow pack due to warmer temperatures and thus less mechanical damages. In middle elevations hardly any changes (class 2) are expected, whereas in lower regions the mortality might show slight increases (class 3) due to increasing temperatures without changing precipitation. For the second assessment period drought is seen to gain importance particularly at lower and middle elevations, and in combination with possibly more frequent and severe forest fires (e.g. Schumacher and Bugmann, 2006) this leads to negative responses (class 3-5) at all elevation stages.

Larix decidua: A similar reasoning is applied like for Norway spruce, but in some points it is somewhat alleviated.

Pinus sylvestris: A similar reasoning is applied like for Norway spruce.

Other coniferous species: cf. *Larix decidua*

Broadleaved: Generally quite similar assumptions like for the other species are made but positive trends (class 1) are expected at higher elevations with regard to abiotic mortality due to warmer temperatures.

Biotic mortality

Picea abies: In general warmer climatic conditions are able to enhance development of poikilothermal insects. Therefore pole and timber stand stages of spruce are seen to be negatively responding with respect to biotic mortality due to increasing pressure by first and foremost bark beetles (e.g. Seidl *et al.* 2006; 2008; 2009). Especially in the lower altitudes and during the 2nd assessment period mortality is expected to increase also due to additional drought stress. In the second period even at high elevations increasing biotic mortality rates (class 3-5) are expected, primarily caused by bark beetles. For youth stages at high elevations mortality is expected to decrease (class 1) due to possibly shorter snow cover durations reducing mortality by snow dependent fungi like for example *Herpotrichia juniperi*.

Larix decidua: In general only minor responses (class 2) have been assumed for larch with regard to biotic mortality. Only the pole and timber stages have been judged to be responding slightly negative (class 3) in the second quite summer dry assessment period due to possibly increasing damages by e.g. *Ips acuminatus* (Battisti, 2004).

Pinus sylvestris: Quite similar like for Norway spruce but a little aggravated due to *Viscum album* infestations fostering drought stress and thus bark beetle infestations as well as effects of other pine pests.

Other coniferous species: A similar reasoning to larch is conducted but for the first period at high elevations a positive trend has been assumed (class 1) for youth and pole stages due to a possible decreasing importance of snow dependent fungal diseases like snow moulds and *Gremmeniella abietina* (Nierhaus-Wunderwald, 1996).

Broadleaved: Hardly any response (class 2) can be projected due to a lack of information.

Regeneration

Picea abies: For the first assessment period at lower and middle altitudes hardly any response (class 2) is expected, whereas in high altitudes positive trends (class 1) are expected due to higher temperatures. In the second period the climate change effects are estimated to be negative due to drier conditions especially at lower (class 4) and middle altitudes (class 3), whereas in higher elevations only negligible responses (class 2) are expected.

Larix decidua: cf. *P. abies*

Pinus sylvestris: For *Pinus sylvestris* the responses to climate change exposure are expected to be of lower magnitude (class 1-2) due to a possible enhancement of regeneration due to drier conditions accompanied by increasing fire activity and senescence of older trees (Hättenschwieler and Körner, 1995). Nevertheless strong decreases in summer precipitation as projected for the second assessment period might counteract this enhancing trend.

Other coniferous species: For the first period a positive trend (class 1) is assumed due to increasing temperatures without precipitation decreases. For the second period hardly any changes (class 2) are expected due to warmer temperatures conflicting with less summer precipitation.

Broadleaved: Higher temperatures might lead to a general enhancement (class 1) of regeneration in the first period. For the second period only minor trends (class 2) are expected at the lower and middle elevation stages due to increasingly dry summer conditions, nevertheless a temperature induced positive response (class 1) is expected for the higher regions.

Tree line

For all species a positive response (class 1) has been assumed for the second assessment period, except of *Pinus sylvestris* which is judged to be insensitive (class 2) as it is hardly occurring at tree line altitudes. For the first assessment period only minor responses (class 2) have been assumed due to system immanent inertia (e.g. Bolli *et al.*, 2007).

As the current state of the forest ecosystem and the responses to climate change exposure have been estimated at assessment unit level they are aggregated to sensitivity estimates according to figure 5. Thereafter they are converted into cardinal values by using the AHP preference values presented in table 5 and figure 6. The full table including all assessment units as well as their area share is available in appendix E - Forest sensitivity assessment tables (Table A 6, Table A 7, Table A 8, Table A 9, Table A 10). To obtain a single value for each indicator the AHP preference values are weighted according to the area share of the assessment unit. After calculating a weighted mean value for each indicator (table 52) forest sensitivity estimates are generated for each protective function according to the weights presented in table 6.

Table 52: Results of the sensitivity assessment on the indicator level presented as AHP preference values (values smaller than 0,63 represent negligible negative or even positive sensitivities, values between 0,63 and 0,89 represent slight to moderate negative sensitivities and values larger than 0,89 are representing strong negative sensitivities).

Indicator	Weighted mean AHP preference value 2035	Weighted mean AHP preference value 2085
Growth	0,38	0,54
Abiotic mortality	0,35	0,76
Biotic mortality	0,49	0,78
Regeneration	0,32	0,37
Tree line	0,32	0,32

The results of this aggregation on the protective function level as well as the conversion into sensitivity classes (cf. table 7) are presented in table 53.

Table 53: Results of the forest sensitivity assessment, cardinal sensitivity values and their conversion into classes according to table 7 (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

Protective function	Cardinal sensitivity value		Sensitivity class	
	2035	2085	2035	2085
Flooding	0,38	0,68	**1**	**2**
Debris flow	0,39	0,68	**1**	**2**
Landslide	0,39	0,68	**1**	**2**
Rock fall	0,38	0,66	**1**	**2**
Avalanche	0,39	0,64	**1**	**2**

Natural hazards

The second part of the sensitivity assessment is to assess the current state and expected natural hazard responses.

The estimates about the current **state** (cf. table 8 and table 9) obtained by interviewing the manager of the management district Oberes Inntal are listed in table 27.

For the assessment of the response of natural hazard frequency (cf. table 46) and magnitude to climate change exposure (cf. table 47) the estimates of the regional manager (table 28) have been considered in addition to results of the literature review. The reasoning conducted in assessing the **response** for the indicators is presented in the following sorted by the respective natural hazard.

Flooding

Frequency: A increase in frequency is assumed (class 3) for the first assessment period due to possibly more abundant precipitation and more frequent torrential rain events. For the second period a strong increase in frequency (class 5) is expected due to a further increase in torrential rain events.

Magnitude: For the first period only negligible responses (class 2) are expected and for the second period a small increase (class 3) is assumed with regard to flood magnitude.

Debris flow

Frequency: A slightly increase in debris flow frequency (class 3) is assumed for the fist assessment period due to possibly more abundant precipitation and more frequent torrential rain events. For the second period a strong increase (class 5) is expected due to further increasing in torrential rain events.

Magnitude: Slightly increasing (class 3) and moderately increasing magnitudes (class 4) are expected for the two assessment periods due to the availability of easily erodible material especially in the regions with calcareous bedrock and at high elevations due to retreating glaciers and permafrost (e.g. Watson and Haeberli, 2004; Chiarle *et al.*, 2007).

Landslide

Frequency: For the two assessment periods a slight increase in frequency (class 3) is assumed due to warmer temperatures (causing permafrost retreat) and more abundant winter precipitation (Beniston, 2005).

Magnitude: For the first assessment period a slight increase in landslide magnitude (class 3) is assumed due to permafrost retreat and winter precipitation increase. For the second period similar assumptions (class 3) are made even as precipitation is projected to decrease under warmer conditions.

Rock fall

Frequency: For the first time slice hardly any response (class 2) is expected for rock fall frequency due to the results of Gruner (2004). For the second assessment period conditions are expected to get worse (class 4) due to intensified torrential rainfall events (Gruner, 2004) and permafrost degradation.

Magnitude: For rock fall magnitude similar assumptions are made like for the frequency (class 2 and 4).

Avalanche

Frequency: For the first assessment period a slight increase in avalanche frequency (class 3) is expected due to increasing winter precipitation, in the second period this situation is assumed to aggravate (class 4) because of a further increase in winter precipitation.

Magnitude: For the first period the magnitude is expected to increase slightly (class 3), whereas for the second period a strong negative response (class 5) is expected due to increasing winter precipitation and extreme snowfall events (assumption Weber).

For each hazardous process and indicator the natural hazard state and response estimates are aggregated according to figure 5, resulting in sensitivity values for each indicator (frequency and magnitude) per natural hazard. The aggregation of the sensitivity values of the two indicators is done by the matrix presented in figure 9. The results of this procedure for the case study region Oberes Inntal are presented in table 54, displaying the sensitivity of all five natural hazards for the two assessment time steps.

Table 54: Results of the natural hazard specific sensitivity assessment (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

Natural hazard	Sensitivity class 2021 - 2050	Sensitivity class 2071 - 2100
Flooding	2	3
Debris flow	3	3
Landslide	3	3
Rock fall	3	3
Avalanche	3	3

4.2.2.2 Potential impacts

To obtain a potential impact estimate for a certain protective function the sensitivities of the forest ecosystem and the natural hazards assessed during the last chapter have to be combined according to the matrix presented in figure 10. The results of this aggregation, the potential impacts on regarded protective functions in the case study area Oberes Inntal, are displayed in table 55 for the two time horizons.

Table 55: Potential impacts, the result of the aggregation of forest and natural hazard sensitivities (1 = hardly any or small negative potential impact, 2 = medium negative potential impact and 3 = strong negative potential impact).

Protective function against	Potential impact 2021 - 2050	Potential impact 2071 - 2100
Flooding	2	3
Debris flow	2	3
Landslide	2	3
Rock fall	2	3
Avalanche	2	3

4.2.2.3 Adaptive capacity

According to the assessment the adaptive capacity of the case study region Oberes Inntal is medium (class 2). The preference values for the single indicators and the aggregated preference values as well as the discretized adaptive capacity class are presented in table 56.

Table 56: Preference values for the single indicators (small values indicate small adaptive capacities and higher values are indicating higher adaptive capacities), weighted preference value as well as the discretized adaptive capacity (class 2 = medium adaptive capacity).

Indicator	Preference value
Road network density	0,457
Share of forest owners <200ha	0,704
Degree of organization and information of small scale owners	0,750
Academic staff BFI	0,712
BFI foresters	0,783
Academic staff WLV	0,705
Office staff WLV	0,807
Production staff WLV	0,729
Budget WLV	0,602
Weighted preference values	0,670
Adaptive capacity class	**2**

4.2.2.4 Vulnerability

After the aggregation of potential impacts and the adaptive capacity according to the vulnerability matrix (figure 13) the final results can be presented (table 57). For the first time step the vulnerabilities are medium for all protective functions and for the second time horizon they are high.

Table 57: Results of the vulnerability assessment for the Upper Inn Valley (class 1 = low, class 2 = medium (2) and class 3 = high vulnerability).

Protective function against	Vulnerability 2021 - 2050	Vulnerability 2071 - 2100
Flooding	2	3
Debris flow	2	3
Landslide	2	3
Rock fall	2	3
Avalanche	2	3

4.2.3 Region C Salzkammergut

4.2.3.1 Sensitivity

The sensitivity assessment is conducted in two steps, first the current state is assessed and thereafter the forest response is judged for each indicator at assessment unit level (cf. chapter 2.4.2.1).

First of all the current **state** of the forest ecosystem is assessed for the Salzkammergut according to the classification presented in table 2.

Growth

Picea abies: Due to the relatively high annual increment of Norway spruce according to the AFI (Anonymous, 1997) a good state (class 1) of the indicator growth is assumed at all elevations.

Fagus sylvatica: According to the low annual increment of beech as reported by the AFI (Anonymous, 1997) a poor state (class 3) of the indicator growth is expected at all elevations.

Other coniferous species: As currently other coniferous species are generating relatively high increment rates the current state of the indicator growth is appraised to be good (class 1) (Anonymous, 1997).

Other broadleaved species: Due to the currently relatively high annual increment the state of the indicator is judged to be good (class 1) (Anonymous, 1997).

Mortality

Due to the low level of detail with respect to the data of the HEM the current state of mortality is judged to be poor (class 3) for all tree species and assessment units. The Salzkammergut case study region has the highest share of damaged timber in the annual felling among the case studies regarded (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b).

Regeneration

Picea abies: Currently regeneration of Norway spruce is expected to be possible at almost all sites and thus the current state is estimated to be good (1) at all elevations with respect to the indicator regeneration.

Fagus sylvatica: The current state of regeneration of beech is estimated to be good (class 1) at elevations lower than 1200m due to favorable climatic conditions. At higher altitudes the current state is assessed to be average (class2).

Other coniferous species: For other coniferous species like *Pinus sylvestris* and *Larix decidua* the current situation of regeneration is assumed to be good (class 1) because of the availability of favorable sites due to recent wind throw events.

Other broadleaved species: At elevations lower than 900m the current state of the indicator regeneration is judged to be good (class1) due to favorable climatic conditions. At higher altitudes it is appraised to be average (class 2).

Tree line

Due to current and abandoned land use practices the actual tree line differs strongly to the potential tree line in some regions of the case study. Therefore an average (class 2) state is assumed for all species except for *Fagus sylvatica* (class 1) as it is currently hardly occurring at tree line altitudes.

The following step is to assess the **responses** of the indicators to climate change exposure. The reasoning applied is presented in the following paragraphs.

Growth

Picea abies: A positive growth trend (class 1) is assumed for the first assessment period at all altitudinal stages due to an increase in temperature and precipitation during the summer months. This assessment has been made according to e.g. Hasenauer *et al.* (1999). For the second time period it is expected that growth at low elevations will moderately decrease (class 4) due to drought stress. In middle elevations it is assumed that growth will be decreasing slightly (class 3), whereas in high elevations growth is seen to increase (class 1) *inter alia* due to the relaxation of the harsh environment in high altitudes (e.g. Paulsen *et al.*, 2000).

Fagus sylvatica: A similar reasoning like for *Picea abies* has been applied.

Other coniferous species: Similar assumptions have been made like for spruce, but as more drought tolerant species (e.g. *Pinus sylvestris*) are involved the judgments have been slightly alleviated.

Other broadleaved species: A positive growth trend (class 1) is assumed for the first assessment period at all altitudinal stages due to an increase in temperature and precipitation during the summer months. For the second time period it is expected that growth at low elevations will moderately decrease (class 4) due to drought stress. In middle elevations it is assumed that growth will be decreasing slightly (class 3) whereas in high elevations growth is expected to increase (class 1) *inter alia* due to the relaxation of the harsh environment in high altitudes (e.g. Paulsen *et al.*, 2000).

Abiotic mortality

Picea abies: With regard to abiotic mortality the response of Norway spruce under the considered exposure is expected to be low for the first assessment period. The response is generally judged as negligible (class 2). For the growth phases youth and pole stage at high elevations a positive trend (class 1) is expected due to shorter snow cover duration and therefore less mechanic damage due to snow gliding and creeping. For the second assessment period abiotic damages are judged to increase slightly to moderately (class 3-4) due to more frequent wind storm events affecting older development phases and decreasing summer precipitation leading to intensified drought stress (e.g. Zebisch *et al.*, 2005).

Fagus sylvatica: For the first assessment period minor only minor responses (class 2) are expected for beech except for the higher regions where a decrease in abiotic mortality (class 1) is assumed due to a relaxation of the harsh environment. For the second assessment period responses are judged to be mostly negative (class 2-4) due to storm and drought intensification at all altitudes.

Other coniferous species: A similar reasoning like for *Picea abies* has been applied, but estimates are a little bit alleviated due to less storm susceptibility of fir, European larch and Scots pine.

Other broadleaved species: A similar reasoning like for beech has been applied.

Biotic mortality

Picea abies: For the first assessment period low to medium increases in biotic mortality (class 3-4) have been assumed for all altitudes due to increasing temperatures enhancing development of poikilothermal insects and slightly increasing summer precipitation. For the second period the increases in biotic mortality are expected to deteriorate (class 3-5) due to increasing mean temperatures and less summer precipitation leading to drought stress predisposing trees to biotic pests and diseases.

Fagus sylvatica: Hardly any response (2) is assumed due to a lack of information.

Other coniferous species: For other coniferous species a comparable reasoning like for *Picea abies* is applied, but the estimates are a little bit alleviated due to higher stress tolerance of e.g. European larch and Scots pine.

Other broadleaved species: cf. *F. sylvatica*.

Regeneration

Picea abies: For the first assessment period at lower and middle altitudes hardly any response (class 2) is expected, whereas in high altitudes a positive response (class 1) is expected due to higher temperatures. In the second period the responses are estimated to be more negative due to drier conditions especially at lower (class 4) and middle altitudes (class 3), whereas in higher elevations only negligible responses (class 2) are expected.

Fagus sylvatica: For the first assessment period at lower and middle altitudes hardly any response (class 2) is expected, whereas in high altitudes the situation is expected to improve (class 1) due to higher temperatures. In the second period the responses are estimated to be more negative due to drier conditions especially at lower altitudes (class 3), whereas in middle altitudes only marginal responses (class 2) are assumed and at higher elevations the situation regarding regeneration is expected to improve (class 1).

Other coniferous species: A comparable reasoning like for *Picea abies* has been applied.

Other broadleaved species: A similar reasoning like for beech has been applied.

Tree line

For the first assessment period only minor responses (class 2) have been assumed due to system immanent inertia (e.g. Bolli *et al.*, 2007), whereas for the second period for all species a positive response (class 1) of the tree line has been assumed, except for *Fagus sylvatica* which is judged to be insensitive with regard to this indicator (class 2) as it is not occurring at tree line altitudes.

As the current state of the forest ecosystem and the sensitivities have been estimated they are aggregated to sensitivity classes according to figure 5 and converted into AHP preference values (cf. chapter 2.4.2.1). The full table including all assessment units as well as their area share is available in appendix E - Forest sensitivity assessment tables (Table A 11, Table A 12, Table A 13, Table A 14, Table A 15). To obtain a single value for each indicator the AHP preference values are weighted according to the area share of the assessment unit. After building a weighted mean value for each indicator (table 58) forest sensitivity estimates are generated for each protective function according to the weights presented in table 6.

Table 58: Results of the sensitivity assessment on the indicator level for the case study region Salzkammergut presented as AHP preference values (values smaller than 0,63 represent negligible negative or even positive sensitivities, values between 0,63 and 0,89 represent slight to moderate negative sensitivities and values larger than 0,89 are representing strong negative sensitivities).

Indicator	Weighted mean AHP preference value 2035	Weighted mean AHP preference value 2085
Growth	0,32	0,67
Abiotic mortality	0,92	0,93
Biotic mortality	0,95	0,95
Regeneration	0,32	0,49
Tree line	0,32	0,32

The results of this aggregation on the protective function level can as well as the conversion into sensitivity classes (cf. table 7) are presented in table 59.

Table 59: Results of the forest sensitivity assessment, cardinal sensitivity values and their conversion into classes according to table 7 (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

Protective function	Cardinal sensitivity value		Sensitivity class	
	2035	2085	2035	2085
Flooding	0,78	0,83	**2**	**2**
Debris flow	0,78	0,82	**2**	**2**
Landslide	0,79	0,83	**2**	**2**
Rock fall	0,73	0,80	**2**	**2**
Avalanche	0,74	0,78	**2**	**2**

Natural hazards

The second part of the sensitivity assessment is to assess the current states and expected responses of the natural hazards.

The estimates about the current **state** (cf. table 8 and table 9) obtained by interviewing the head of the management district Salzkammergut are listed in table 36.

For the assessment of the response of natural hazard frequency (cf. table 46) and magnitude (cf. table 47) to climate change exposure the estimates of the regional manager (table 37) have been considered in addition to results of the literature review. The reasoning conducted in assessing the **response** of the indicators is presented in the following ordered by natural hazard.

Flooding

Frequency: For the first assessment period hardly any response (class 2) is expected, whereas for the second period a slight increase in flood frequency (class 3) is expected due to more frequent torrential rain events.

Magnitude: For both assessment periods a slight increase (class 3) with respect to flood magnitudes is expected.

Debris flow

A similar reasoning like for flooding is applied, as these processes are often interlinked and triggered by similar conditions.

Landslide

Frequency: For the first assessment period a slight increase in frequency (class 3) is expected due to increasing summer and winter precipitation. For the second period only minor responses (class 2) are assumed as only winter precipitation tends to increase, accompanied by increasing temperatures reducing water storage in the snow pack (Dehn, 1999).

Magnitude: Hardly any response to climate change exposure (class 2) with regard to land slide magnitude is expected.

Rock fall

Frequency: For the first period hardly any response (class 2) is expected due to warming conditions reducing joint expansion. For the second period a small increase in rock fall frequency (class 3) is assumed due to the possibility of more frequent and severe torrential rain events (Gruner, 2004).

Magnitude: A similar reasoning like for rock fall frequency is applied.

Avalanche

Frequency: Hardly any response (class 2) is expected with regard to frequency for the first assessment period. For the second period a slight increase in avalanche frequency (class 3) is expected due to increasing winter precipitation.

Magnitude: For the first period only negligible responses (class 2) are assumed and for the second period a moderate increase in avalanche magnitude (class 4) is expected due to more winter precipitation.

For each hazardous process and indicator the state and response estimates are aggregated according to figure 5, resulting in two sensitivity estimates (frequency and magnitude) for each natural hazard. The aggregation of the sensitivity estimates for these two indicators is done by the matrix presented in figure 9. The results of this procedure for the case study region Salzkammergut are presented in table 60, displaying the sensitivity of all five natural hazards for the two assessment time steps.

Table 60: Results of the natural hazard specific sensitivity assessment (1 = negligible negative or even positive sensitivity, 2 = slight to moderate negative sensitivity and 3 = strong negative sensitivity).

Natural hazard	Sensitivity class 2021 - 2050	Sensitivity class 2071 - 2100
Flooding	2	3
Debris flow	2	2
Landslide	3	3
Rock fall	3	3
Avalanche	1	3

4.2.3.2 Potential impacts

To obtain a potential impact estimate for a certain protective function the sensitivities of the forest ecosystem and the natural hazards assessed during the last chapter have to be combined according to the matrix presented in figure 10. The results of this aggregation, the potential impacts on regarded protective functions in the case study area Salzkammergut, can be seen in table 61 for the two time horizons.

Table 61: Potential impact classes as the result of the aggregation of forest and natural hazard sensitivities (1 = hardly any or small negative potential impact, 2 = medium negative potential impact and 3 = strong negative potential impact).

Protective function against	Potential impact 2021 - 2050	Potential impact 2071 - 2100
Flooding	2	3
Debris flow	2	2
Landslide	2	3
Rock fall	2	3
Avalanche	1	3

4.2.3.3 Adaptive capacity

According to the assessment the adaptive capacity of the case study region Salzkammergut is medium (class 2). The preference values for the single indicators and the aggregated preference values as well as the discretized adaptive capacity class are presented in table 62.

Table 62: Preference values for the single indicators (small values indicate small adaptive capacities and higher values are indicating higher adaptive capacities), weighted preference value as well as the discretized adaptive capacity (class 2 = medium adaptive capacity).

Indicator	Preference value
Road network density	0,585
Share of forest owners <200ha	0,733
Degree of organization and information of small scale owners	0,500
Academic staff BFI	0,229
BFI foresters	0,139
Academic staff WLV	0,867
Office staff WLV	0,822
Production staff WLV	0,547
Budget WLV	0,273
Weighted preference values	0,523
Adaptive capacity class	**2**

4.2.3.4 Vulnerability

After the aggregation of potential impacts and adaptive capacity according to the vulnerability matrix (figure 13) the final results can be presented (table 63). For the first time step the vulnerability is low for the protection against avalanches, medium for the protection against flooding and debris flow and high for the protection against landslide and rock fall. For the second time horizon all protection functions are highly vulnerable except the protection against debris flows which remains on the medium vulnerability level.

Table 63: Results of the vulnerability assessment for the Salzkammergut (class 1 = low, class 2 = medium (2) and class 3 = high vulnerability).

Protective function against	Vulnerability 2021 - 2050	Vulnerability 2071 - 2100
Flooding	2	3
Debris flow	2	2
Landslide	3	3
Rock fall	3	3
Avalanche	1	3

4.3 Adaptation options in forest management

This chapter refers to the results of the literature review concerning adaptation options in forest management. Possible adaptation options for mountain forests will be presented. Europe's mountain forests are rich in diversity of forest types and socio-economic conditions. The owner-structure and related interests of owners and stakeholders do not allow for one-fits-all solutions. Local and regional assessment of vulnerabilities and adaptation measures are crucial to identify efficient and cost-effective adaptation strategies (Lindner *et al.*, 2008). Therefore the following adaptation measures have to be seen as possible options in adapting forest management.

To provide structured results the adaptation options found in literature have been classified in eight groups with respect to all stages of forest management and spatial scales from stand level to higher scales.

(i) Forest regeneration,

(ii) Tending of stands,

(iii) Harvesting,

(iv) Management planning,

(v) Forest protection,

(vi) Infrastructure and transport,

(vii) Nurseries and forest tree breeding, and

(viii) Higher level adaptation options in risk management and policy.

In general it has to be stated that conclusive targeted research results on adaptation options in mountainous regions are scarce especially with regard to adaptation of protective forests. Adaptation options presented in the scientific literature are mostly recommendations made on the basis of climate change impact studies missing explicit design and analysis for adaptation. The main focus of presented adaptation options has been Central Europe with emphasis on the European Alps.

4.3.1 Forest regeneration

Forest regeneration is a key to long-term adaptation measures. Major hotspots of adverse impacts of changing climatic conditions are stands with species compositions maladapted to the site already under current climate. In such stands, often monocultures, change of species composition is of high priority in climate change adaptation. Particular examples are secondary coniferous forests in the pre-alpine areas and alpine foothills. Within given species the choice of reproductive plant material for stand conversion is highly important and should be made explicitly considering climate change (Zebisch *et al.*, 2005). In this context according to Geburek (1994) two strategies can be applied regarding forest reproductive material. First, forest reproductive material of high genetic diversity may be used which has a high genetic adaptability (for similar arguments see also Spiecker, 2003; Zebisch *et al.*, 2005). Second, forest reproductive material which is adapted to the projected conditions can be promoted, even if this leads to stands which are adapted in a suboptimal way to current conditions (Geburek, 1994). The latter option is of considerable risk considering the high uncertainties in projections of future climate.

Wherever possible, natural regeneration is to be enhanced because evolutionary processes are less disturbed. However, this requires that the gene pool of available seed trees is suitable for the site. Furthermore regeneration patches should be small and the regeneration phase should be as long as possible to achieve a high genetic diversity (Geburek, 1994). Spiecker (2003) agrees on recommending natural regeneration in small gaps and the avoidance of large scale clear cuts as adaptation options. Natural regeneration is also a cost efficient way to regenerate forests.

However, natural regeneration can be unsuitable e.g. due to an intended change in tree species composition or a lack of suitable seed trees. As stated before the choice of forest reproductive material is crucial for artificial regeneration too (Geburek, 1994). It is recommended to use a wide initial spacing and drought tolerant species and provenances to counteract drought stress in drought prone areas (Spiecker, 2003) even though the genetic diversity at stand level might be reduced.

The establishment of “pioneer populations” (i.e. species populations outside their current areal) could enhance the migration of tree species under climate change. Pioneer populations could be established via planting species in regions where they do not yet occur, but where future conditions are expected to be favorable for the selected species (Müller, 1994).

Of great importance for forest regeneration is that successful establishment and early growth of young stands may be strongly influenced by soil preparation, selection of species and provenances, quality of plant material and weed control, factors that might gain importance in ensuring successful regeneration under climatic changes (Kellomäki *et al.*, 2000; Spiecker, 2003).

Müller (1994) proposes to enrich stands with tree species which are likely to be able to cope better with climate change. He suggests tree species like *Betula pendula*, *Populus tremula*, *Alnus sp*. but also *Pinus sylvestris*, *Pinus nigra*, *Larix decidua*, *Quercus sp.*, *Carpinus betulus* and *Tilia cordata*. Furthermore, he expects that exotic species like *Pseudotsuga menziesii*, *Robinia pseudoacacia*, *Quercus rubra* and *Juglans sp.* will perform better under projected climatic conditions which are drier than today than *Fagus sylvatica* and *Picea abies*. The author states that a broader species mix including these species will enhance future flexibility in forest management (Müller, 1994). However, the introduction of neophytes is also associated with risks and threats. For instance, native biodiversity may be substantially reduced (Spiecker, 2003). Although well adapted to dry and warm conditions, an especially aggressive species in this respect is *Robinia pseudoacacia* (Walter *et al.*, 2005).

4.3.2 Tending of stands

To ensure a high genetic variability thinnings should be carried out systematically, disregarding any qualitative aspects, like it is proposed for genetic reserves (Food and Agriculture Organization, 1992). However, this is in strong contrast to current thinning guidelines in Central Europe recommending selective thinning approaches. According to Müller (1994) stands should be managed in a way that enhances structural richness in age, diameter, height, species distribution, etc. Such management is assumed to be able to increase stability by reducing large scale susceptibility to disturbances. Especially protective functions would be supported by an increase in structural diversity (Müller, 1994). Management adjustments will also be required to account for accelerating growth rates due to more favorable growing conditions in a warmer climate particularly in mountain areas to control average growing stock and subsequently the stability of forests (Spiecker, 2003).

For Swiss protective forests Bürgi and Brang (2001) are stating that already the current standing stock is too high. With regard to climate change adaptation they recommend to reduce the standing stock via tending, thinning and harvesting in order to enhance regeneration. As a side effect, proper silvicultural techniques provided, the stability of stands e.g. against wind throw could be increased. It is stated that such a reduction in growing stock has to be carried out very carefully to produce the desired effects. With respect to protective forests, regeneration should be fostered in over-aged forests (Bürgi and Brang, 2001).

According to Spiecker (2003) tending of young stands should foster mixed stands. Furthermore, intensified thinning treatments should result in an increased total harvest. A side effect of this recommendation is, *inter alia*, to increase the proportion of large-dimensioned timber on the total harvest volume. Additionally, intensified thinning may have some effect on site productivity by altering the nutrient cycle and reducing competition for light, nutrients and water. At drought prone sites more intensive thinnings are reducing stand evapotranspiration and thus counteracting increasing drought stress (Spiecker, 2003; Kellomäki *et al.*, 2000).

4.3.3 Harvesting

For adaptation options solely focusing on harvesting of timber no sources could be identified. However, the general adaptation options described for thinning operations above might be also valid for harvesting to some extent.

4.3.4 Management planning

According to Noss (2001, p. 578) “[…] Good forest management in a time of rapidly changing climate differs little from good forest management under more static conditions, but there is increased emphasis on protecting climatic refugia and providing connectivity. […]”

However, other authors see substantial need for altered planning and management systems. Spiecker (2003) states that new planning and decision tools have to be applied to deal with uncertainty and risk in long-term forest planning. Traditional anticipation of goals and means, on the one hand, may not be adequate when managing forests under risk and uncertainty. Therefore flexible adaptive planning, which takes into account all conceivable scenarios and allows multiple options for future development may be the best suited alternative (von Gadow, 2000). Furthermore, there is a demand for forestry to be adaptive to future societal demands, providing multiple functions sustainably in the future. The complexity of the decision problems evolving from this situation show that solutions have to be developed in a multi- and transdisciplinary cooperation of scientists and decision makers. Such cooperations will lead to a more comprehensive understanding of the complex problems involved in decision making and will provide a more realistic and reliable basis for decision support for management in future forest ecosystems (Spiecker, 2003).

But not only planning has to be improved under climate change. Bürgi and Brang (2001) highlight the necessity of an effective controlling in forest management, which is getting even more important under climate change conditions and is a key component of adaptive management (e.g. Rauscher, 1999).

At the level of technical recommendations several recommendations regarding forest management planning are proposed. In drought prone regions a shortening of rotation periods might be an adequate means for overcoming the projected rapid pace of climate change (Kellomäki *et al.*, 2000; Spiecker, 2003).

Mixed stands have been found to be more resistant against various forms of damage than pure single-species stands (cf. chapter 4.3.1). Furthermore changing from monocultures to mixed stands will alter the conditions for growth by affecting the root systems, litter quality, nutrient cycling, carbon storage and soil acidity (Spiecker, 2003). These measures are not only relevant with regard to climate change adaptation but can be highly beneficial for the performance of forests with regard to their functions in general.

Conducting a simulation study on silvicultural concepts in an inner alpine basin in Austria Lexer *et al.* (2006) are concluding that converting secondary coniferous forests into mixed stands can be beneficial under climate change. The main effects found in their simulation study are (a) better response of growth of broadleaved species under projected climate change conditions, and (b) the increasing predisposition of *Picea abies* to biotic disturbances such as by *Ips typographus* (Lexer *et al.*, 2006; Seidl *et al.*, 2008). Continuous cover forestry is proposed as a management alternative by some authors and found beneficial in simulations studies with regard to some forest functions like for example protection (e.g. Spiecker 2003). However, Seidl *et al.* (2008) also demonstrated high disturbance risk of a pure Norway spruce continuous cover system with a continuity of high standing stock.

Another option to avoid additional stress on forest trees is the preservation of soil fertility, e.g. by liming and by minimizing soil compaction (Zebisch *et al.*, 2005).

4.3.5 Forest protection

Badeck *et al.* (2004) are stating that development of forest fire prevention and warning systems should be fostered. Stand conversion to mixed broadleaved forests will support forest fire prevention due to more moist bioclimatic conditions within the stand (Badeck *et al.*, 2004). In general most of the adaptation measures presented will have direct or indirect effect on forest protection, although often only indirectly.

4.3.6 Infrastructure and transport

For Central European forests Zebisch *et al.* (2005) state that, in drought prone areas, measures should be taken to prevent decreasing ground water tables. For instance, they propose the restoration of the water regime in e.g. floodplain forests or the deactivation of drainage systems (Zebisch *et al.*, 2005).

Although not highlighted in literature the development of an appropriate road network is very important for mountain forestry to ensure the proposed small scale management activities (cf. chapter 4.3.1) and to provide accessibility necessary for sanitation fellings. Both aspects are of particular importance for management of protective forests.

Also not indicated in scientific literature is the importance of infrastructure for round timber storage after large scale wind throws. For this purpose wet or foil storage facilities should be prepared for fast disturbance mitigation to prevent pest outbreaks and to disburden the wood market (Odenthal-Kahabka, 2005).

4.3.7 Nurseries and tree breeding

For nurseries and tree breeding some valuable recommendations have been made already in the section on forest regeneration, which are also valid for the production of forest reproductive material. Again it has to be emphasized that the choice of forest reproductive material, in this case the seeds (high genetic adaptability or adaptation to projected conditions), is most important for climate change adaptation (Geburek, 1994). For tree breeding under climatic changes no mountain-forest specific adaptation options are reported.

4.3.8 Higher level adaptation options in risk management and policy

Müller (1994) proposes to establish forest reserves for the investigation and monitoring of climate change impacts which can be valuable for science and development of adaptation strategies. This is also supported by Noss (2001) and Spiecker (2003) conducting reviews on forest management under climate change.

Furthermore, it is recommended to reduce forest fragmentation in some areas through afforestation and by establishing connecting corridors between densely forested regions (Spiecker, 2003). This is particularly important in the complex terrain of alpine landscapes.

Zebisch *et al.* (2005) emphasize the increasing importance of a consistent risk management in forestry. This could be promoted by enhancing human capital though e.g., training courses. The focus should lie on identification, prophylaxis and prevention of risks and furthermore on mitigation of occurred damages (Zebisch *et al.*, 2005).

5 Discussion

5.1 Knowledge base and climate projections

The results of the literature review are indicating strong differences in quantity and quality of studies investigating climate change and its effect on forested ecosystems and the goods and services provided by them. A lot of information is available with respect to timber production and carbon sequestration (Lindner *et al.*, 2008). Other services like the provision of drinking water or the protection against natural hazards are investigated significantly less intensively. But not only information on climate change impacts on forest goods and services is unbalanced, similar findings are true for key ecosystem processes such as growth, regeneration and mortality of trees and their sensitivity to climate change. Plenty of information is available for climate change effects on forest growth and yield. Less information is available with regard to mortality although certain pests like *Ips typographus* are investigated quite well with regard to potential behavior under climate change (e.g. Baier *et al.*, 2007). Interactions of climate change, growth, bark beetles and forest management are investigated, for instance, by Seidl *et al.* (2006; 2008; 2009). For fungal diseases hardly any information is available, though with respect to protective forests climate change implications for snow dependent fungal diseases like *Herpotrichia juniperi*, *Phacidium infestans* or *Gremmeniella abietina* would be of great interest. Targeted studies focusing on natural regeneration processes under climate change are very rare, however some studies on implications of drought on artificial regeneration have just been started (Rigling *et al.*, 2008).

With regard to natural hazards, compared to available research results for forest ecosystems, considerably less scientific information is available regarding climate change sensitivities. Intensive research has been carried out at high altitudes investigating hazards connected to climate change induced permafrost and glacier retreat, but targeted research on future developments below the timberline are scarce. To some extent this might be due to the difficulties in projecting extreme events with current climate models, as natural hazards are mostly triggered by extreme weather conditions in regions which are not characterized by permafrost or glaciers.

Therefore a vulnerability assessment of forest protective functions is affected by considerable uncertainties which originate from a limited knowledge base with regard to the response of relevant hazardous processes in a changing climate. As natural hazardous processes are mostly triggered by extreme weather conditions climate change projections including information about extreme events are key elements in improved vulnerability assessments. Thus transient regional climate change scenarios with a daily resolution allowing the analysis of extreme events at least for 24 hour periods would enhance estimations about the future development of frequency and magnitude of natural hazards.

With regard to forest ecosystems future windstorm patterns and magnitudes would be also of large interest, as wind throw is heavily affecting the functionality of forest stands especially for protection.

5.2 Methodology

With regard to the methodology it was not intended to conduct a simulation based vulnerability assessment as the high level of detail which is needed to apply regional assessments can not be handled in a fast and efficient way. The efforts required to implement such studies are considerable regarding (a) the need to calibrate impact models, (b) data needs to initialize and drive impact models, and (c) the know how required to apply and interpret output of impact models properly. The latter point is particularly important if the degree of integration in such an assessment is low and relatively easy model application is traded in against potential caveats in interpreting output of parallel model applications (see Lexer and Seidl, 2009).

Therefore, the current study proposes a fast and flexible assessment at regional scale which borrows from approaches such as rapid rural appraisals (e.g., Chambers, 1992; Ison and Ampt, 1992; Pereira *et al.*, 2005) and builds on a qualitative approach based on regional data, expert interviews and evidence from the literature. For the sake of simplicity ordinal scales are used for the assessments whenever possible, however, when different thematic and geographic levels have to be aggregated a cardinal scaling was chosen to allow additive aggregations.

The choice of indicators is of major importance for the assessment of sensitivities as well as for the assessment of the adaptive capacity. With regard to sensitivity the indicator set is kept simple but well balanced. The indicators used to assess the regional adaptive capacity are of particular interest. The reasons therefore are twofold. On the one hand the concept of adaptive capacity is rather complex, e.g. with regard to the system boundaries including the socio-economic domain. On the other hand the information basis for some indicators is rather poor or they are difficult to assess, as for example the share of subsidies granted in a certain region for forest management and the effectiveness of those subsidies. Hence, the investigation of regional adaptive capacities remains a topic worthwhile to be investigated, as with regard to protective functions of mountain forests under climate change hardly any research work has yet been done.

5.3 Case studies

With regard to the potential impacts considerable differences exist between the three case studies (Table 64). The lowest potential impacts are found for the Upper Mur Valley, where even in the second assessment period beyond 2071 no strong negative potential impacts are expected. A major reason therefore might be that the forest ecosystem sensitivities are judged to be marginally negative or even positive as biotic mortality is the only indicator showing negative sensitivities because of expected increases in bark beetle infestations. The generally favorable assessment result for the Upper Mur Valley is due to hardly any projected precipitation change for the summer months in both time horizons tending to result in improving or stable conditions for all other indicators. In contrast to that, the other two case studies are expected to encounter considerable precipitation decreases for the summer months in the second assessment period.

For the Upper Inn Valley for the period from 2021 to 2050 medium negative potential impacts are estimated and for the period beyond 2071 the results show strong negative potential impacts. The projected decrease in precipitation during the summer months of the second assessment period might account for that trend to some extent. Due to the expected drier conditions abiotic (forest fires) and biotic mortality (bark beetles) may increase. Furthermore growth is expected to decrease in the altitudinal zones below 1200 m and regeneration for species such as e.g. *Picea abies* will be negatively affected at lower altitudes due to drought.

The potential impacts found for the Salzkammergut are somewhat contrasting as already in the first period from 2021 to 2050 strong negative potential impacts are expected for the protection against landslides and rock fall. This is mainly due to high frequencies and magnitudes of hazards already under current climate. Furthermore, to some extent the rather unfavorable results for the Salzkammergut are also due to the climate change exposure projecting increasing drought for the second time period and due to already currently very high shares (>40%) of salvaged timber in the annual felling (Anonymous, 2002b, 2003, 2004, 2005, 2006, 2007, 2008, 2009b). But it has to be stated that for a regional assessment more spatially explicit information concerning damaged timber in the annual felling would be welcome as information on provincial level is not able to represent regional patterns of e.g. wind throw events or bark beetle gradations. In addition the case study region Salzkammergut is characterized by a major area share of forests under 900m (66%) stocked by Norway spruce (55%). This leads to rather negative results with regard to forest sensitivity already in the period from 2021 to 2050 (slight to moderate negative sensitivities) due to expected increases in wind throw and bark beetle infestations.

Table 64: Potential impacts on the protective functions for the three case study regions in comparison (1 = hardly any or small negative potential impact, 2 = medium negative potential impact and 3 = strong negative potential impact).

Protective function	Upper Mur Valley		Upper Inn Valley		Salzkammergut	
	2021-2050	2071-2100	2021-2050	2071-2100	2021-2050	2071-2100
Flooding	2	2	2	3	2	3
Debris flow	2	2	2	3	2	2
Rock fall	1	1	2	3	3	3
Landslide	1	2	2	3	3	3
Avalanche	1	2	2	3	1	3

With regard to the results of the adaptive capacity a homogeneous picture can be drawn as for all three regions adaptive capacity (AC) is estimated as intermediate (cf. table 50, table 56, and table 62). However, when looking at the cardinal values (compare table 50, table 56, and table 62) differences between the regions can be observed. The highest value (0,67 on a scale between 0 and 1) and therefore most positive value is estimated for the Upper Inn Valley, ranked first in a comparison between the regions. Second is the Salzkammergut with AC = 0,52 right in the centre of the intermediate class, and ranked third is the Upper Mur Valley with an estimate of AC = 0,34. Due to the broad definition of the intermediate AC category no differentiation takes place between the three regions. This may be seen as a serious limitation. However, the approach of having a fairly narrow definition of good and bad conditions has the advantage of reduced uncertainty for regions being placed in these classes. This advantage comes at the cost of having potentially many regions placed in the broad intermediate category. Due to the quite unspecific regional estimates of AC the results of the vulnerability assessment are showing the same pattern and magnitude as the potential impacts (table 2).

Table 65: Vulnerabilities of the protective functions for the three case study regions in comparison (1 = low vulnerability, 2 = medium vulnerability and 3 = high vulnerability).

Protective function	Upper Mur Valley		Upper Inn Valley		Salzkammergut	
	2021-2050	2071-2100	2021-2050	2071-2100	2021-2050	2071-2100
Flooding	2	2	2	3	2	3
Debris flow	2	2	2	3	2	2
Rock fall	1	1	2	3	3	3
Landslide	1	2	2	3	3	3
Avalanche	1	2	2	3	1	3

Major goal of the current work was the development of a scheme for regional vulnerability assessment of forest protective functions. No sensitivity analysis with regard to the appraisal has been made. Thus the results for the three case studies should be seen as a possible future development subject to multi-level uncertainty.

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6.3 Personal communications

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7 Appendix

A - Index of figures

B - Index of tables

C - Index of tables used in the appendix

D – Interview guideline

Interviewleitfaden Gebietsbauleitung

Allgemeines

Gebietsbauleitung: ____________________

Gebietsbauleiter: ____________________

Interviewpartner: ____________________

Datum: ____________________

Charakteristika der Gebietsbauleitung

Fläche: ____________________

Bezirke/ BFIs: ____________________

Mitarbeiter: ____________________

Akademiker: ____________________

Technisch-administratives Personal: ____________________

Arbeiter/ Bauhof: ____________________

Jahresbudget: ____________________

Naturgefahren

- Hochwasser/ Wildbach
- Mure
- Hangrutschung
- Steinschlag
- Lawine

Derzeitige Relevanz der Naturgefahren

Frequenz potentieller Schadereignisse:
1. Seltene Ereignisse. < 1 (<5) Mal jährlich
2. Häufige Ereignisse. 1 bis 10 (5 bis 20) Mal jährlich
3. Sehr häufige Ereignisse. > 10 (>20) Mal jährlich

Magnitude potentieller Schadereignisse:

1. Kleine Ereignisse. Kaum Schadpotential (punktuelle Unterbrechung von Verkehrswegen)

2. Mittlere Ereignisse. Mittleres Schadpotential (Unterbrechung von Verkehrswegen, Beschädigung/ Zerstörung einzelner Gebäude)

3. Große Ereignisse. Hohes Schadpotential (Zerstörung von Verkehrswegen und Ansiedelungen)

Naturgefahr BL	**Frequenz**	**Magnitude**
Hochwasser		
Mure		
Hangrutschung		
Steinschlag		
Lawine		

Einschätzung der Entwicklung der Naturgefahren im Klimawandel

Klimaszenario A1B (2085)

Temperaturerhöhung:

Sommerniederschlag

Winterniederschlag (DJF):

Jahresniederschlag:

+…	positive Entwicklung
o…	gleichbleibend
-…	leichte Verschlechterung
--…	mittlere Verschlechterung
---…	starke Verschlechterung erwartet.

Naturgefahr CC	**Frequenz**	**Magnitude**
Hochwasser		
Mure		
Hangrutschung		
Steinschlag		
Lawine		

E - Forest sensitivity assessment tables

In this part of the appendix the tables used for the forest sensitivity assessment are presented.

Upper Mur Valley

Table A 1: Table used to assess the sensitivity of the indicator growth for the Upper Mur Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	0,051	0,051	**1**	**1**	1	**0,317**	**3**	1	**0,317**
	900-1200	0,242	0,242	**1**	**1**	1	**0,317**	**2**	1	**0,317**
	>1200	0,518	0,518	**1**	**1**	1	**0,317**	**1**	1	**0,317**
Larix decidua	<900	0,002	0,002	**1**	**1**	1	**0,317**	**2**	1	**0,317**
	900-1200	0,025	0,025	**1**	**1**	1	**0,317**	**1**	1	**0,317**
	>1200	0,075	0,075	**1**	**1**	1	**0,317**	**1**	1	**0,317**
Other coniferous	<900	0,000	0,000	**3**	**1**	1	**0,317**	**2**	3	**0,947**
	900-1200	0,000	0,000	**3**	**1**	1	**0,317**	**1**	1	**0,317**
	>1200	0,025	0,025	**3**	**1**	1	**0,317**	**1**	1	**0,317**
Broadleaved	<900	0,014	0,014	**3**	**1**	1	**0,317**	**1**	1	**0,317**
	900-1200	0,033	0,033	**3**	**1**	1	**0,317**	**1**	1	**0,317**
	>1200	0,014	0,014	**3**	**1**	1	**0,317**	**1**	1	**0,317**
Accumulated cardinal sensitivity - growth							**0,317**			**0,317**

Table A 2: Table used to assess the sensitivity of the indicator abiotic mortality for the Upper Mur Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	growth phase	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
						response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	youth	0,007	0,010	2	2	1	0,317	2	1	0,317
	900-1200	youth	0,033	0,055	2	2	1	0,317	2	1	0,317
	>1200	youth	0,064	0,106	2	1	1	0,317	1	1	0,317
	<900	pole	0,017	0,013	2	2	1	0,317	2	1	0,317
	900-1200	pole	0,061	0,049	2	2	1	0,317	2	1	0,317
	>1200	pole	0,172	0,142	2	1	1	0,317	1	1	0,317
	<900	timber	0,027	0,028	2	2	1	0,317	2	1	0,317
	900-1200	timber	0,147	0,137	2	2	1	0,317	2	1	0,317
	>1200	timber	0,282	0,270	2	2	1	0,317	2	1	0,317
Larix decidua	<900	youth	0,000	0,000	2	2	1	0,317	2	1	0,317
	900-1200	youth	0,003	0,006	2	2	1	0,317	2	1	0,317
	>1200	youth	0,009	0,015	2	1	1	0,317	1	1	0,317
	<900	pole	0,001	0,001	2	2	1	0,317	2	1	0,317
	900-1200	pole	0,006	0,005	2	2	1	0,317	2	1	0,317
	>1200	pole	0,025	0,021	2	1	1	0,317	1	1	0,317
	<900	timber	0,001	0,001	2	2	1	0,317	2	1	0,317
	900-1200	timber	0,015	0,014	2	2	1	0,317	2	1	0,317
	>1200	timber	0,041	0,039	2	2	1	0,317	2	1	0,317
Other coniferous	<900	youth	0,000	0,000							
	900-1200	youth	0,000	0,000							
	>1200	youth	0,003	0,005	2	1	1	0,317	1	1	0,317
	<900	pole	0,000	0,000							
	900-1200	pole	0,000	0,000							
	>1200	pole	0,008	0,007	2	1	1	0,317	1	1	0,317
	<900	timber	0,000	0,000							
	900-1200	timber	0,000	0,000							
	>1200	timber	0,013	0,013	2	2	1	0,317	2	1	0,317
Broadleaved	<900	youth	0,002	0,003	2	2	1	0,317	2	1	0,317
	900-1200	youth	0,004	0,007	2	1	1	0,317	2	1	0,317
	>1200	youth	0,002	0,003	2	1	1	0,317	1	1	0,317
	<900	pole	0,005	0,004	2	2	1	0,317	2	1	0,317
	900-1200	pole	0,008	0,007	2	1	1	0,317	2	1	0,317
	>1200	pole	0,005	0,004	2	1	1	0,317	1	1	0,317
	<900	timber	0,008	0,008	2	2	1	0,317	2	1	0,317
	900-1200	timber	0,020	0,018	2	1	1	0,317	2	1	0,317
	>1200	timber	0,008	0,008	2	1	1	0,317	1	1	0,317
Accumulated cardinal sensitivity - abiotic mortality								**0,317**			**0,317**

Table A 3: Table used to assess the sensitivity of the indicator biotic mortality for the Upper Mur Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	growth phase	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
						response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	youth	0,007	0,010	2	2	1	0,317	3	2	0,764
	900-1200	youth	0,033	0,055	2	2	1	0,317	2	1	0,317
	>1200	youth	0,064	0,106	2	1	1	0,317	1	1	0,317
	<900	pole	0,017	0,013	2	3	2	0,764	4	3	0,947
	900-1200	pole	0,061	0,049	2	2	1	0,317	4	3	0,947
	>1200	pole	0,172	0,142	2	2	1	0,317	3	2	0,764
	<900	timber	0,027	0,028	2	3	2	0,764	5	3	0,947
	900-1200	timber	0,147	0,137	2	3	2	0,764	4	3	0,947
	>1200	timber	0,282	0,270	2	3	2	0,764	4	3	0,947
Larix decidua	<900	youth	0,000	0,000	2	2	1	0,317	2	1	0,317
	900-1200	youth	0,003	0,006	2	2	1	0,317	2	1	0,317
	>1200	youth	0,009	0,015	2	2	1	0,317	2	1	0,317
	<900	pole	0,001	0,001	2	2	1	0,317	3	2	0,764
	900-1200	pole	0,006	0,005	2	2	1	0,317	3	2	0,764
	>1200	pole	0,025	0,021	2	2	1	0,317	2	1	0,317
	<900	timber	0,001	0,001	2	2	1	0,317	3	2	0,764
	900-1200	timber	0,015	0,014	2	2	1	0,317	3	2	0,764
	>1200	timber	0,041	0,039	2	2	1	0,317	2	1	0,317
Other coniferous	<900	youth	0,000	0,000							
	900-1200	youth	0,000	0,000							
	>1200	youth	0,003	0,005	2	1	1	0,317	1	1	0,317
	<900	pole	0,000	0,000							
	900-1200	pole	0,000	0,000							
	>1200	pole	0,008	0,007	2	1	1	0,317	2	1	0,317
	<900	timber	0,000	0,000							
	900-1200	timber	0,000	0,000							
	>1200	timber	0,013	0,013	2	1	1	0,317	2	1	0,317
Broadleaved	<900	youth	0,002	0,003	2	2	1	0,317	2	1	0,317
	900-1200	youth	0,004	0,007	2	2	1	0,317	2	1	0,317
	>1200	youth	0,002	0,003	2	2	1	0,317	2	1	0,317
	<900	pole	0,005	0,004	2	2	1	0,317	2	1	0,317
	900-1200	pole	0,008	0,007	2	2	1	0,317	2	1	0,317
	>1200	pole	0,005	0,004	2	2	1	0,317	2	1	0,317
	<900	timber	0,008	0,008	2	2	1	0,317	2	1	0,317
	900-1200	timber	0,020	0,018	2	2	1	0,317	2	1	0,317
	>1200	timber	0,008	0,008	2	2	1	0,317	2	1	0,317
Accumulated cardinal sensitivity - biotic mortality								**0,528**			**0,708**

Table A 4: Table used to assess the sensitivity of the indicator regeneration for the Upper Mur Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	0,051	0,051	**1**	**2**	1	**0,317**	**2**	1	**0,317**
	900-1200	0,242	0,242	**1**	**2**	1	**0,317**	**2**	1	**0,317**
	>1200	0,518	0,518	**1**	**1**	1	**0,317**	**1**	1	**0,317**
Larix decidua	<900	0,002	0,002	**1**	**2**	1	**0,317**	**2**	1	**0,317**
	900-1200	0,025	0,025	**1**	**2**	1	**0,317**	**2**	1	**0,317**
	>1200	0,075	0,075	**1**	**1**	1	**0,317**	**1**	1	**0,317**
Other coniferous	<900	0,000	0,000							
	900-1200	0,000	0,000							
	>1200	0,025	0,025	**2**	**1**	1	**0,317**	**1**	1	**0,317**
Broadleaved	<900	0,014	0,014	**1**	**2**	1	**0,317**	**2**	1	**0,317**
	900-1200	0,033	0,033	**2**	**1**	1	**0,317**	**1**	1	**0,317**
	>1200	0,014	0,014	**3**	**1**	1	**0,317**	**1**	1	**0,317**
Accumulated cardinal sensitivity - regeneration							**0,317**			**0,317**

Table A 5: Table used to assess the sensitivity of the indicator tree line for the Upper Mur Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	>1200	0,518	0,518	**2**	**2**	1	**0,317**	**1**	1	**0,317**
Larix decidua	>1200	0,075	0,075	**2**	**2**	1	**0,317**	**1**	1	**0,317**
Other coniferous	>1200	0,025	0,025	**2**	**2**	1	**0,317**	**1**	1	**0,317**
Broadleaved	>1200	0,014	0,014	**2**	**2**	1	**0,317**	**1**	1	**0,317**
Accumulated cardinal sensitivity - tree line							**0,317**			**0,317**

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Table A 6: Table used to assess the sensitivity of the indicator growth for the Upper Inn Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	0,058	0,058	**2**	**2**	1	**0,317**	**5**	3	**0,947**
	900-1200	0,064	0,064	**2**	**2**	1	**0,317**	**3**	2	**0,764**
	>1200	0,506	0,506	**2**	**1**	1	**0,317**	**2**	1	**0,317**
Larix decidua	<900	0,008	0,008	**2**	**2**	1	**0,317**	**4**	3	**0,947**
	900-1200	0,019	0,019	**2**	**2**	2	**0,764**	**3**	2	**0,764**
	>1200	0,098	0,098	**2**	**1**	1	**0,317**	**2**	1	**0,317**
Pinus sylvestris	<900	0,007	0,007	**3**	**2**	3	**0,947**	**5**	3	**0,947**
	900-1200	0,074	0,074	**3**	**2**	3	**0,947**	**3**	3	**0,947**
	>1200	0,054	0,054	**3**	**1**	1	**0,317**	**2**	3	**0,947**
Other coniferous	<900	0,000	0,000	**3**	**2**	3	**0,947**	**5**	3	**0,947**
	900-1200	0,000	0,000	**3**	**2**	3	**0,947**	**3**	3	**0,947**
	>1200	0,071	0,071	**3**	**1**	1	**0,317**	**2**	3	**0,947**
Broadleaved	<900	0,015	0,015	**2**	**2**	1	**0,317**	**3**	2	**0,764**
	900-1200	0,008	0,008	**2**	**1**	2	**0,764**	**3**	2	**0,764**
	>1200	0,017	0,017	**2**	**1**	1	**0,317**	**1**	1	**0,317**
Accumulated cardinal sensitivity - growth							**0,380**			**0,536**

Table A 7: Table used to assess the sensitivity of the indicator abiotic mortality for the Upper Inn Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	growth phase	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
						response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	youth	0,004	0,009	2	3	2	0,764	5	3	0,947
	900-1200	youth	0,004	0,011	2	2	1	0,317	3	2	0,764
	>1200	youth	0,037	0,034	2	1	1	0,317	3	2	0,764
	<900	pole	0,032	0,007	2	3	2	0,764	4	3	0,947
	900-1200	pole	0,034	0,004	2	2	1	0,317	3	2	0,764
	>1200	pole	0,283	0,065	2	1	1	0,317	3	2	0,764
	<900	timber	0,021	0,042	2	3	2	0,764	4	3	0,947
	900-1200	timber	0,026	0,049	2	2	1	0,317	3	2	0,764
	>1200	timber	0,186	0,407	2	2	1	0,317	3	2	0,764
Larix decidua	<900	youth	0,001	0,001	2	3	2	0,764	4	3	0,947
	900-1200	youth	0,001	0,003	2	2	1	0,317	3	2	0,764
	>1200	youth	0,007	0,007	2	1	1	0,317	3	2	0,764
	<900	pole	0,005	0,001	2	2	1	0,317	3	2	0,764
	900-1200	pole	0,010	0,001	2	2	1	0,317	3	2	0,764
	>1200	pole	0,055	0,013	2	1	1	0,317	3	2	0,764
	<900	timber	0,003	0,006	2	2	1	0,317	3	2	0,764
	900-1200	timber	0,008	0,014	2	2	1	0,317	3	2	0,764
	>1200	timber	0,036	0,079	2	2	1	0,317	3	2	0,764
Pinus sylvestris	<900	youth	0,000	0,001	2	3	2	0,764	5	3	0,947
	900-1200	youth	0,005	0,013	2	2	1	0,317	3	2	0,764
	>1200	youth	0,004	0,004	2	1	1	0,317	3	2	0,764
	<900	pole	0,004	0,001	2	3	2	0,764	4	3	0,947
	900-1200	pole	0,039	0,005	2	2	1	0,317	3	2	0,764
	>1200	pole	0,030	0,007	2	1	1	0,317	3	2	0,764
	<900	timber	0,003	0,005	2	3	2	0,764	4	3	0,947
	900-1200	timber	0,030	0,056	2	2	1	0,317	3	2	0,764
	>1200	timber	0,020	0,044	2	2	1	0,317	3	2	0,764
Other coniferous	<900	youth	0,000	0,000							
	900-1200	youth	0,000	0,000							
	>1200	youth	0,005	0,005	2	1	1	0,317	3	2	0,764
	<900	pole	0,000	0,000							
	900-1200	pole	0,000	0,000							
	>1200	pole	0,040	0,009	2	1	1	0,317	3	2	0,764
	<900	timber	0,000	0,000							
	900-1200	timber	0,000	0,000							
	>1200	timber	0,026	0,057	2	2	1	0,317	3	2	0,764
Broadleaved	<900	youth	0,001	0,002	2	3	2	0,764	3	2	0,764
	900-1200	youth	0,001	0,001	2	2	1	0,317	3	2	0,764
	>1200	youth	0,001	0,001	2	1	1	0,317	1	1	0,317
	<900	pole	0,009	0,002	2	2	1	0,317	3	2	0,764
	900-1200	pole	0,004	0,001	2	2	1	0,317	2	1	0,317
	>1200	pole	0,009	0,002	2	1	1	0,317	1	1	0,317
	<900	timber	0,006	0,011	2	2	1	0,317	3	2	0,764
	900-1200	timber	0,003	0,006	2	2	1	0,317	2	1	0,317
	>1200	timber	0,006	0,014	2	1	1	0,317	1	1	0,317
Accumulated cardinal sensitivity - abiotic mortality								**0,346**			**0,765**

Table A 8: Table used to assess the sensitivity of the indicator biotic mortality for the Upper Inn Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	growth phase	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
						response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	youth	0,004	0,009	2	3	2	0,764	3	2	0,764
	900-1200	youth	0,004	0,011	2	2	1	0,317	2	1	0,317
	>1200	youth	0,037	0,034	2	1	1	0,317	2	1	0,317
	<900	pole	0,032	0,007	2	3	2	0,764	4	3	0,947
	900-1200	pole	0,034	0,004	2	3	2	0,764	4	3	0,947
	>1200	pole	0,283	0,065	2	2	1	0,317	3	2	0,764
	<900	timber	0,021	0,042	2	3	2	0,764	5	3	0,947
	900-1200	timber	0,026	0,049	2	3	2	0,764	4	3	0,947
	>1200	timber	0,186	0,407	2	3	2	0,764	4	3	0,947
Larix decidua	<900	youth	0,001	0,001	2	2	1	0,317	2	1	0,317
	900-1200	youth	0,001	0,003	2	2	1	0,317	2	1	0,317
	>1200	youth	0,007	0,007	2	2	1	0,317	2	1	0,317
	<900	pole	0,005	0,001	2	2	1	0,317	3	2	0,764
	900-1200	pole	0,010	0,001	2	2	1	0,317	3	2	0,764
	>1200	pole	0,055	0,013	2	2	1	0,317	3	2	0,764
	<900	timber	0,003	0,006	2	2	1	0,317	3	2	0,764
	900-1200	timber	0,008	0,014	2	2	1	0,317	3	2	0,764
	>1200	timber	0,036	0,079	2	2	1	0,317	3	2	0,764
Pinus sylvestris	<900	youth	0,000	0,001	2	3	2	0,764	3	2	0,764
	900-1200	youth	0,005	0,013	2	2	1	0,317	2	1	0,317
	>1200	youth	0,004	0,004	2	1	1	0,317	2	1	0,317
	<900	pole	0,004	0,001	2	3	2	0,764	4	3	0,947
	900-1200	pole	0,039	0,005	2	3	2	0,764	4	3	0,947
	>1200	pole	0,030	0,007	2	2	1	0,317	2	1	0,317
	<900	timber	0,003	0,005	2	3	2	0,764	5	3	0,947
	900-1200	timber	0,030	0,056	2	3	2	0,764	5	3	0,947
	>1200	timber	0,020	0,044	2	2	1	0,317	3	2	0,764
Other coniferous	<900	youth	0,000	0,000							
	900-1200	youth	0,000	0,000							
	>1200	youth	0,005	0,005	2	1	1	0,317	2	1	0,317
	<900	pole	0,000	0,000							
	900-1200	pole	0,000	0,000							
	>1200	pole	0,040	0,009	2	1	1	0,317	2	1	0,317
	<900	timber	0,000	0,000							
	900-1200	timber	0,000	0,000							
	>1200	timber	0,026	0,057	2	2	1	0,317	2	1	0,317
Broadleaved	<900	youth	0,001	0,002	2	2	1	0,317	2	1	0,317
	900-1200	youth	0,001	0,001	2	2	1	0,317	2	1	0,317
	>1200	youth	0,001	0,001	2	2	1	0,317	2	1	0,317
	<900	pole	0,009	0,002	2	2	1	0,317	2	1	0,317
	900-1200	pole	0,004	0,001	2	2	1	0,317	2	1	0,317
	>1200	pole	0,009	0,002	2	2	1	0,317	2	1	0,317
	<900	timber	0,006	0,011	2	2	1	0,317	2	1	0,317
	900-1200	timber	0,003	0,006	2	2	1	0,317	2	1	0,317
	>1200	timber	0,006	0,014	2	2	1	0,317	2	1	0,317
Accumulated cardinal sensitivity - biotic mortality								**0,487**			**0,783**

Table A 9: Table used to assess the sensitivity of the indicator regeneration for the Upper Inn Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	0,058	0,058	2	2	1	0,317	4	3	0,947
	900-1200	0,064	0,064	1	2	1	0,317	3	1	0,317
	>1200	0,506	0,506	1	1	1	0,317	2	1	0,317
Larix decidua	<900	0,008	0,008	2	2	1	0,317	4	3	0,947
	900-1200	0,019	0,019	1	2	1	0,317	3	1	0,317
	>1200	0,098	0,098	1	1	1	0,317	2	1	0,317
Pinus sylvestris	<900	0,007	0,007	1	2	1	0,317	2	1	0,317
	900-1200	0,074	0,074	1	2	1	0,317	2	1	0,317
	>1200	0,054	0,054	1	1	1	0,317	1	1	0,317
Other coniferous	<900	0,000	0,000							
	900-1200	0,000	0,000							
	>1200	0,071	0,071	2	1	1	0,317	2	1	0,317
Broadleaved	<900	0,015	0,015	1	2	1	0,317	4	2	0,764
	900-1200	0,008	0,008	2	1	1	0,317	2	2	0,764
	>1200	0,017	0,017	3	1	1	0,317	1	1	0,317
Accumulated cardinal sensitivity - regeneration							0,317			0,369

Table A 10: Table used to assess the sensitivity of the indicator tree line for the Upper Inn Valley, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	>1200	0,506	0,506	2	2	1	0,317	1	1	0,317
Larix decidua	>1200	0,098	0,098	2	2	1	0,317	1	1	0,317
Pinus sylvestris	>1200	0,054	0,054	1	2	1	0,317	2	1	0,317
Other coniferous	>1200	0,071	0,071	2	2	1	0,317	1	1	0,317
Broadleaved	>1200	0,017	0,017	2	2	1	0,317	1	1	0,317
Accumulated cardinal sensitivity - tree line							0,317			0,317

Salzkammergut

Table A 11: Table used to assess the sensitivity of the indicator growth for the Salzkammergut, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	0,366	0,366	**1**	**1**	1	**0,317**	**4**	2	**0,764**
	900-1200	0,135	0,135	**1**	**1**	1	**0,317**	**3**	1	**0,317**
	>1200	0,060	0,060	**1**	**1**	1	**0,317**	**2**	1	**0,317**
Fagus sylvatica	<900	0,186	0,186	**3**	**1**	1	**0,317**	**4**	3	**0,947**
	900-1200	0,104	0,104	**3**	**1**	1	**0,317**	**3**	3	**0,947**
	>1200	0,008	0,008	**3**	**1**	1	**0,317**	**2**	3	**0,947**
Other coniferous	<900	0,029	0,029	**1**	**1**	1	**0,317**	**3**	1	**0,317**
	900-1200	0,020	0,020	**1**	**1**	1	**0,317**	**3**	1	**0,317**
	>1200	0,003	0,003	**1**	**1**	1	**0,317**	**2**	1	**0,317**
Other broadleaved	<900	0,084	0,084	**1**	**1**	1	**0,317**	**2**	1	**0,317**
	900-1200	0,004	0,004	**1**	**1**	1	**0,317**	**3**	1	**0,317**
	>1200	0,001	0,001	**1**	**1**	1	**0,317**	**2**	1	**0,317**
Accumulated cardinal sensitivity - growth							**0,317**			**0,668**

Table A 12: Table used to assess the sensitivity of the indicator abiotic mortality for the Salzkammergut, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	growth phase	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
						response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	youth	0,046	0,078	3	2	3	0,947	4	3	0,947
	900-1200	youth	0,016	0,028	3	2	3	0,947	3	3	0,947
	>1200	youth	0,005	0,010	3	1	1	0,317	1	1	0,317
	<900	pole	0,141	0,076	3	2	3	0,947	3	3	0,947
	900-1200	pole	0,044	0,023	3	2	3	0,947	2	3	0,947
	>1200	pole	0,027	0,014	3	1	1	0,317	1	1	0,317
	<900	timber	0,179	0,211	3	2	3	0,947	4	3	0,947
	900-1200	timber	0,075	0,083	3	2	3	0,947	4	3	0,947
	>1200	timber	0,028	0,036	3	2	3	0,947	3	3	0,947
Fagus sylvatica	<900	youth	0,024	0,040	3	2	3	0,947	4	3	0,947
	900-1200	youth	0,013	0,022	3	2	3	0,947	3	3	0,947
	>1200	youth	0,001	0,001	3	1	1	0,317	2	3	0,947
	<900	pole	0,071	0,039	3	2	3	0,947	3	3	0,947
	900-1200	pole	0,034	0,018	3	2	3	0,947	2	3	0,947
	>1200	pole	0,004	0,002	3	1	1	0,317	2	3	0,947
	<900	timber	0,091	0,107	3	2	3	0,947	3	3	0,947
	900-1200	timber	0,058	0,064	3	2	3	0,947	3	3	0,947
	>1200	timber	0,004	0,005	3	1	1	0,317	3	3	0,947
Other coniferous	<900	youth	0,004	0,006	3	2	3	0,947	4	3	0,947
	900-1200	youth	0,002	0,004	3	2	3	0,947	3	3	0,947
	>1200	youth	0,000	0,000	3	1	1	0,317	1	1	0,317
	<900	pole	0,011	0,006	3	2	3	0,947	3	3	0,947
	900-1200	pole	0,006	0,003	3	2	3	0,947	2	3	0,947
	>1200	pole	0,001	0,001	3	1	1	0,317	1	1	0,317
	<900	timber	0,014	0,017	3	2	3	0,947	3	3	0,947
	900-1200	timber	0,011	0,012	3	2	3	0,947	3	3	0,947
	>1200	timber	0,001	0,002	3	2	3	0,947	3	3	0,947
Other broadleaved	<900	youth	0,011	0,018	3	2	3	0,947	4	3	0,947
	900-1200	youth	0,000	0,001	3	2	3	0,947	3	3	0,947
	>1200	youth	0,000	0,000	3	1	1	0,317	1	1	0,317
	<900	pole	0,032	0,018	3	2	3	0,947	3	3	0,947
	900-1200	pole	0,001	0,001	3	2	3	0,947	2	3	0,947
	>1200	pole	0,001	0,000	3	1	1	0,317	2	3	0,947
	<900	timber	0,041	0,049	3	2	3	0,947	3	3	0,947
	900-1200	timber	0,002	0,002	3	2	3	0,947	3	3	0,947
	>1200	timber	0,001	0,001	3	1	1	0,317	3	3	0,947
Accumulated cardinal sensitivity - abiotic mortality								**0,920**			**0,931**

Table A 13: Table used to assess the sensitivity of the indicator biotic mortality for the Salzkammergut, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	growth phase	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
						response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	youth	0,046	0,078	3	3	3	0,947	4	3	0,947
	900-1200	youth	0,016	0,028	3	3	3	0,947	3	3	0,947
	>1200	youth	0,005	0,010	3	2	3	0,947	2	3	0,947
	<900	pole	0,141	0,076	3	4	3	0,947	5	3	0,947
	900-1200	pole	0,044	0,023	3	3	3	0,947	4	3	0,947
	>1200	pole	0,027	0,014	3	2	3	0,947	4	3	0,947
	<900	timber	0,179	0,211	3	4	3	0,947	5	3	0,947
	900-1200	timber	0,075	0,083	3	4	3	0,947	5	3	0,947
	>1200	timber	0,028	0,036	3	2	3	0,947	4	3	0,947
Fagus sylvatica	<900	youth	0,024	0,040	3	2	3	0,947	2	3	0,947
	900-1200	youth	0,013	0,022	3	2	3	0,947	2	3	0,947
	>1200	youth	0,001	0,001	3	2	3	0,947	2	3	0,947
	<900	pole	0,071	0,039	3	2	3	0,947	2	3	0,947
	900-1200	pole	0,034	0,018	3	2	3	0,947	2	3	0,947
	>1200	pole	0,004	0,002	3	2	3	0,947	2	3	0,947
	<900	timber	0,091	0,107	3	2	3	0,947	2	3	0,947
	900-1200	timber	0,058	0,064	3	2	3	0,947	2	3	0,947
	>1200	timber	0,004	0,005	3	2	3	0,947	2	3	0,947
Other coniferous	<900	youth	0,004	0,006	3	3	3	0,947	4	3	0,947
	900-1200	youth	0,002	0,004	3	3	3	0,947	3	3	0,947
	>1200	youth	0,000	0,000	3	2	3	0,947	2	3	0,947
	<900	pole	0,011	0,006	3	4	3	0,947	5	3	0,947
	900-1200	pole	0,006	0,003	3	3	3	0,947	4	3	0,947
	>1200	pole	0,001	0,001	3	2	3	0,947	3	3	0,947
	<900	timber	0,014	0,017	3	4	3	0,947	5	3	0,947
	900-1200	timber	0,011	0,012	3	3	3	0,947	4	3	0,947
	>1200	timber	0,001	0,002	3	2	3	0,947	3	3	0,947
Other broadleaved	<900	youth	0,011	0,018	3	2	3	0,947	2	3	0,947
	900-1200	youth	0,000	0,001	3	2	3	0,947	2	3	0,947
	>1200	youth	0,000	0,000	3	2	3	0,947	2	3	0,947
	<900	pole	0,032	0,018	3	2	3	0,947	2	3	0,947
	900-1200	pole	0,001	0,001	3	2	3	0,947	2	3	0,947
	>1200	pole	0,001	0,000	3	2	3	0,947	2	3	0,947
	<900	timber	0,041	0,049	3	2	3	0,947	2	3	0,947
	900-1200	timber	0,002	0,002	3	2	3	0,947	2	3	0,947
	>1200	timber	0,001	0,001	3	2	3	0,947	2	3	0,947
Accumulated cardinal sensitivity - biotic mortality								**0,947**			**0,947**

Table A 14: Table used to assess the sensitivity of the indicator regeneration for the Salzkammergut, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	<900	0,366	0,366	**1**	**2**	1	**0,317**	**4**	2	**0,764**
	900-1200	0,135	0,135	**1**	**2**	1	**0,317**	**3**	1	**0,317**
	>1200	0,060	0,060	**1**	**1**	1	**0,317**	**2**	1	**0,317**
Fagus sylvatica	<900	0,186	0,186	**1**	**2**	1	**0,317**	**3**	1	**0,317**
	900-1200	0,104	0,104	**1**	**2**	1	**0,317**	**2**	1	**0,317**
	>1200	0,008	0,008	**2**	**1**	1	**0,317**	**1**	1	**0,317**
Other coniferous	<900	0,029	0,029	**1**	**2**	1	**0,317**	**4**	2	**0,764**
	900-1200	0,020	0,020	**1**	**2**	1	**0,317**	**3**	1	**0,317**
	>1200	0,003	0,003	**1**	**1**	1	**0,317**	**2**	1	**0,317**
Other broadleaved	<900	0,084	0,084	**1**	**2**	1	**0,317**	**3**	1	**0,317**
	900-1200	0,004	0,004	**2**	**2**	1	**0,317**	**2**	1	**0,317**
	>1200	0,001	0,001	**2**	**1**	1	**0,317**	**1**	1	**0,317**
Accumulated cardinal sensitivity - regeneration							**0,317**			**0,493**

Table A 15: Table used to assess the sensitivity of the indicator tree line for the Salzkammergut, featuring area shares, state and response estimates as well as the resulting ordinal and cardinal sensitivity estimates for the two time horizons.

Species	altitudinal zone	area share 2021 - 2050	area share 2071 - 2100	state	2021 - 2050			2071 - 2100		
					response	ordinal sensitivity	cardinal sensitivity	response	ordinal sensitivity	cardinal sensitivity
Picea abies	>1200	0,060	0,060	**2**	**2**	1	**0,317**	**1**	1	**0,317**
Fagus sylvatica	>1200	0,008	0,008	**1**	**2**	1	**0,317**	**2**	1	**0,317**
Other coniferous	>1200	0,003	0,003	**2**	**2**	1	**0,317**	**1**	1	**0,317**
Other broadleaved	>1200	0,001	0,001	**2**	**2**	1	**0,317**	**1**	1	**0,317**
Accumulated cardinal sensitivity - tree line							**0,317**			**0,317**