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## Synthesis on main outcomes of the simulation on the effects of Forest Management Alternatives (FMA) on forest damage indicators

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# D2.4.6 - Synthesis report on main outcomes of simulation on effects of forest management alternatives (FMA) on forest damage indicators

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## Abstract

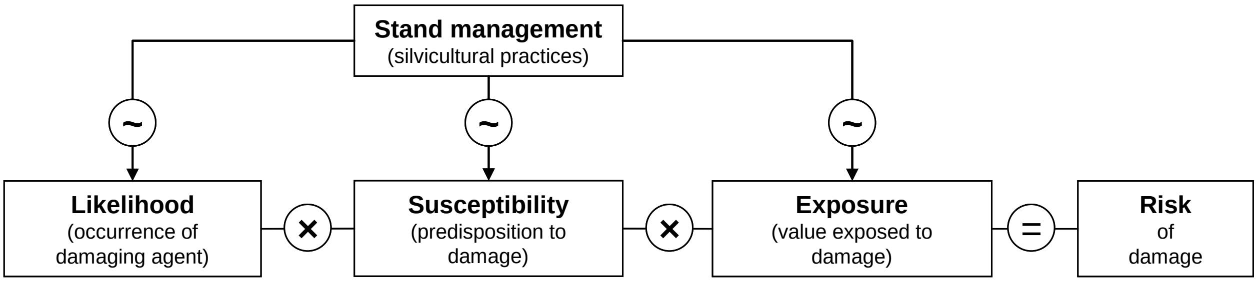
Multi-criteria decision analysis (MCDA) has been developed to help decision makers choose between actions that require reaching a compromise between criteria of different weights. We adapted this method to evaluate the effect of a range of forest management alternatives (FMA) – as defined by the European Integrated Project Eforwood – on risks for forest health. Risk is defined as the interaction between forest vulnerability (a combination of susceptibility and exposure) to a hazard and the likelihood of the hazard occurring. Specific forest vulnerabilities to a series of abiotic (wind, fire and snow) and biotic (insect pests, pathogenic fungi and herbivores) hazards were defined and subsequently weighted by corresponding hazard likelihood. Multi-criteria risk analyses (MCRA) were applied to eight types of managed forests in Europe (three forest biomes: Atlantic, Continental and Boreal, and five tree species: Scots pine, maritime pine, Norway spruce, Sitka spruce and *Eucalyptus* sp.) to rank FMAs according to their potential effect on forest health at the stand level. Overall, risk was lower in intensively managed short rotation forests, designed to produce wood biomass, because of the reduced susceptibility of stands to the most damaging hazards. At the opposite end of the management intensity gradient, close-to-nature systems also had low overall risk, this time due to lower stand exposure to damage. Intensive even-aged forestry appeared to be subject to the greatest risk, irrespective of tree species and bioclimatic zone. These results seem to be robust as no significant differences in relative ranking of four FMAs were detected between the eight types of European managed forest.

*Key words:* risk analysis, multi criteria, hazards, biotic, abiotic, forest damage, forest management alternatives.

# Table of contents

# 1 Introduction

One of the main purpose of the Eforwood project was to evaluate the impact of a range of stand management alternatives on forest resources and the forestry wood chain. Wood production may be impaired by natural disturbances. It is therefore of great importance to estimate the influence of forest management on the risk of damage (Jactel et al. 2009). Risk is defined as the interaction between hazard likelihood, susceptibility and exposure, and forest management may have an effect on all three components of the risk of damage.




Equations or quantitative models can be developed to evaluate risk for a particular hazard in a particular area if likelihood, susceptibility and exposure have been quantified, for example as probability of occurrence, probability of damage and loss values. However it is rarely the case in forestry. It is even more complicated to evaluate risk of damage in forest when several hazards, i.e. causes of damage, have to be taken into account. It is therefore almost impossible to quantitatively predict the effect of new management practices (alternatives) on overall risk in European forests. Nevertheless one may be able to provide semi-quantitative estimates of hazard likelihood, susceptibility and exposure, for example using scores. The question remains about how to combine the effects of several damaging agents but the Multi Criteria Decision Analysis (MCDA) method may offer an appropriate way to solve this problem.

Multi-criteria decision analysis (MCDA) has been developed to help decision makers choose between actions that require reaching a compromise between decision criteria that have different weightings (e.g. balancing financial return from timber sales against non-market benefits from biodiversity and recreation). We have adapted this methodology to design a Multi Criteria Risk Analysis (MCRA) approach (see PD 2.4.5 – Jactel et al, 2008 for details).

We need to compare the potential effect on forest health of different forest management alternatives (FMAs): it is exactly as if forest managers would have to make a choice between different actions, i.e. decide about which FMA to apply. To make their decision, forest managers will have to consider the risks each FMA might result in. Forest Management Alternatives are designed according to main objectives – or forest functions, such as wood production or environmental services – and they are described as a combination of stand management practices (see EFORWOOD D 2.1.3). FMA's objectives can be used to qualify stand exposure to biotic and abiotic hazards. For example, a forest intensively managed to produce the maximum of biomass (FMA "Wood Biomass Production") will experience a greater impact of hazards that reduce wood production such as bark beetles or fire; it is more exposed to these hazards. FMA's practices can be used to estimate stand susceptibility to biotic and abiotic hazards as demonstrated in the EFORWOOD D 2.4.3. The interaction between exposure and susceptibility is often defined as vulnerability. To make a decision about FMAs forest managers will have to consider their vulnerability to several main types of biotic and abiotic hazards (pest insects, diseases, wind, fire etc.): we will therefore consider these vulnerabilities as criteria to compare FMAs. But not all of the hazards have the same occurrence in a given area, depending on local climate or intrinsic species dynamics. We will then use the likelihood of a hazard to weight the importance of stand vulnerability to this hazard, just as criteria have weights in Multi Criteria Decision Analysis. Correspondences between MCDA and MCRA approaches are summarized in Table 1.

**Table 1** Correspondences between objectives and vocabulary of Multi Criteria Decision Analysis and Multi Criteria Risk Analysis

| **MCDA** | **MCRA** |
|---|---|
| Solve a decision problem | Solve a forest management problem |
| Rank actions in order of increasing preference according to several criteria | Rank FMAs in order of increasing risk of damage by several hazards |
| Action | Forest Management Alternative |
| Criterion | Susceptibility or Vulnerability to one hazard |
| Weight | Likelihood of the hazard |

## 2 Method

We considered 8 forest types as a combination of regions (Atlantic Portugal, Aquitaine in France, Baden-Württemberg in Germany, Scotland, central Austria, Silesia in Poland, and central Sweden) and tree species (Eucalyptus, maritime pine, Scots pine, Sitka spruce and Norway spruce) (Figure 1). In each forest type we considered the 5 most frequent biotic and abiotic hazards, including wind, fire, frost, insect borers and defoliators, leaf and root pathogens, as risk criteria (Table 2).

**Table 2** List of case studies used in the MCRA and hazard criteria

| **Country/Region** | **Tree species** | **5 criteria (most frequent damaging agents)** | | | | |
|---|---|---|---|---|---|---|
| Portugal/Atlantic | *Eucalyptus globulus* | leaf rust | leaf beetle | gall insect | fire | stem canker |
| France/Aquitaine | *Pinus pinaster* | defoliator | stem borer | wind | fire | root rot |
| Baden-Württemberg | *Picea abies* | root rot | wind | bark beetle | snow | game |
| Austria | *Picea abies* | bark beetle | wind | snow | game | sawfly |
| Scotland | *Picea sitchensis* | game | wind | weevil | aphid | fire |
| Scotland | *Pinus sylvestris* | game | wind | weevil | foliar disease | fire |
| Poland/Silesia | *Pinus sylvestris* | game | root rot | weevil | sawfly | wind |
| Sweden | *Pinus sylvestris* | root rot | weevil | game | bark beetle | wind |


**Figure 1** Location of the cases studies

In each forest type we compared 4 FMAs along a gradient of increasing silviculture intensity (Close-to-Nature, Combined Objectives, Intensive Even-Aged, Wood Biomass production) as defined in the EFORWOOD PD 2.1.3 (Duncker and all, 2007). We did not consider the unmanaged forest nature reserve (FMA 1) because it has limited relevance for wood supply in Europe. For each FMA we defined the main silvicultural operations allocated to each management option. Eight successive stand management actions were considered for each forest management alternative: site selection, soil preparation, tree species selection, tree genotype selection, regeneration, understorey management, tree thinning and pruning, final harvesting. Forest management silvicultural operations usually performed in each forest type were produced by experts on silviculture, under the European Integrated Project Eforwood, based on what forest managers usually practice in the respective area.

In each region, we gathered a panel of at least one expert per criterion (hazard type) to evaluate the effect of each option on stand susceptibility to each hazard, giving a number of at least three experts for each region.
First, the experts evaluated the susceptibility of the forest produced by the alternative forest silvicultural operations associated to each forest management option in regard to each disturbance factor. The following procedure was used: for each stand management action, the experts identified the options that had no effect on tree susceptibility to a specific hazard. These options were used as

a reference standards and a score of 1 was given to these options. Then the experts gave a score of 0.50 or 0.75 to any option that would greatly or moderately decrease stand susceptibility, respectively and a score of 1.25 or 1.50 if it would moderately or greatly increase stand susceptibility, respectively, as compared to the reference standards (Table 3). Then for each FMA, scores were averaged across actions for each hazard.
The scoring was made independently from the other region to avoid any bias.

**Table 3** Method of scoring forest stand susceptibility to specific hazards

| Effect of silvicultural option on stand susceptibility to hazard | Score |
|---|---|
| Greatly decrease stand susceptibility | 0.50 |
| Moderately decrease stand susceptibility | 0.75 |
| No effect | 1.00 |
| Moderately increase stand susceptibility | 1.25 |
| Greatly increase stand susceptibility | 1.50 |

The complete list of scores is provided in Appendix 1.

To evaluate stand exposure to hazards we considered 3 types of forest damage indicators (tree mortality, loss in biomass production, loss in wood quality), and scored their relative importance for each FMA, using a five levels scale: 0, 0.25, 0.50, 0.75, and 1 for null, low, moderate, high and very high respectively. The complete list of scores is given in Appendix 2.


**Figure 3** Example of scoring for importance of damage types in *Pinus pinaster* stands in Aquitaine

As a sensitivity analysis, we tested another range of scores for the relative importance of the three types of damage, differing by three orders of magnitude. For the loss in wood quality we used scores varying from 0 to 1, for the loss in biomass production the scores varied from 0 to 10 and for tree mortality the scores could vary from 0 to 100. This option will be referred as “uneven impact” whereas the option with the same range of scores for all types of damage will be referred as ‘even impact” thereafter.

We estimated the contribution of hazards to the three damage types, using a five levels scale: 0, 0.25, 0.50, 0.75, and 1 for null, low, moderate, high and very high respectively. In principle, the contribution of a particular hazard to a particular type of damage was considered as constant, irrespective of stand management. The complete list of scores is given in Appendix 3.

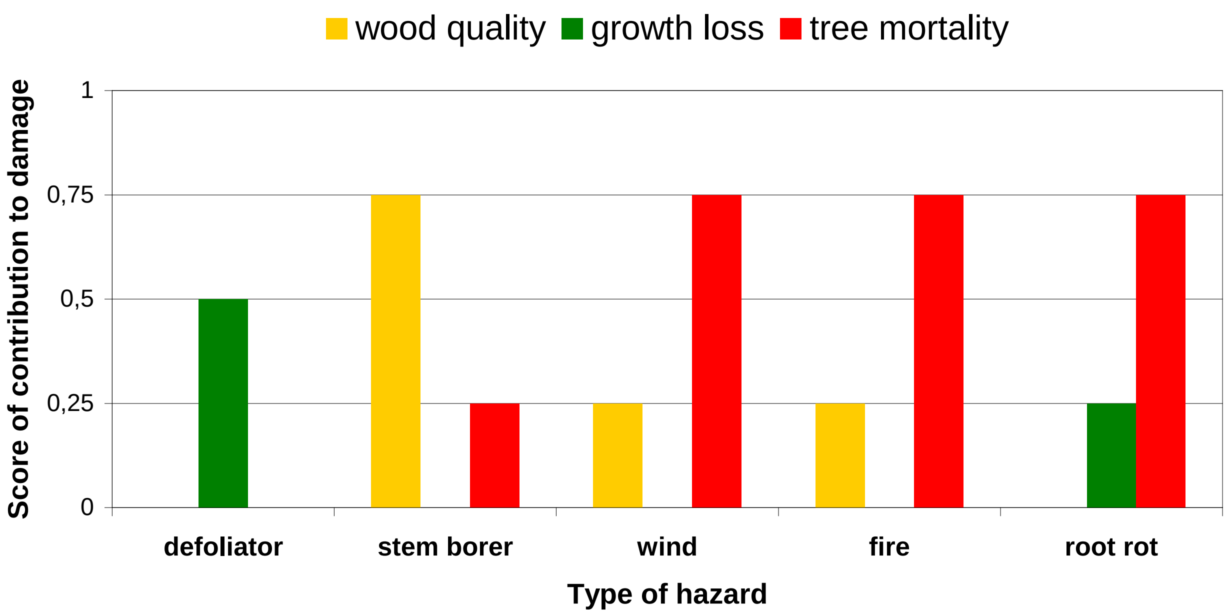



**Figure 4** Example of scoring for contribution of main hazards to damage types in *Pinus pinaster* stands in Aquitaine

We combined the contribution of main hazards to the three damage types to the importance of these damage types for each Forest Management Alternative to score the exposure of each FMA to each hazard, by multiplying scores in figure 4 by those in figure 5. We averaged scores across damage types for each hazard to estimate a main exposure to each hazard. The complete list of scores is given in Appendix 4 for both “even” and “uneven” impacts of damage.

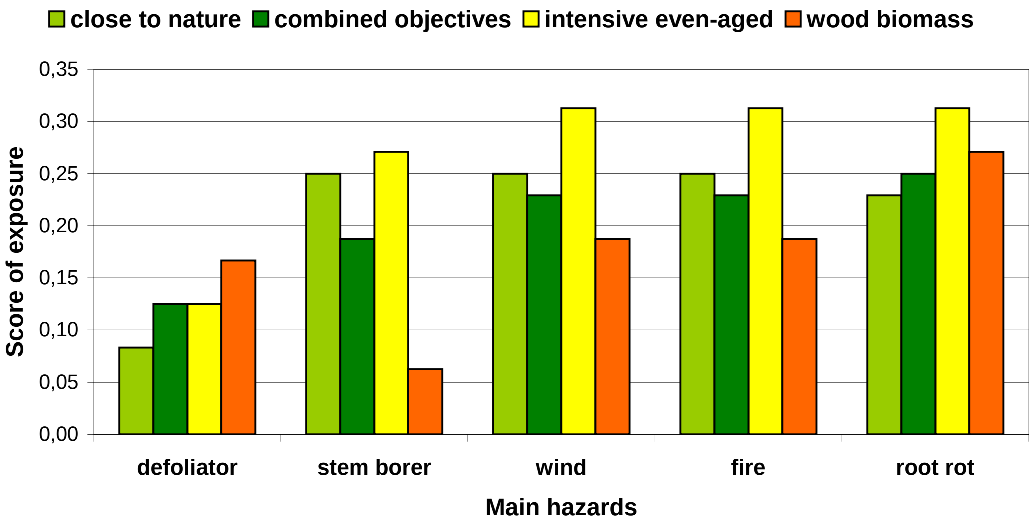



**Figure 5-a** Example of scoring for exposure of *Pinus pinaster* stands to the main hazards in Aquitaine (Even impact)

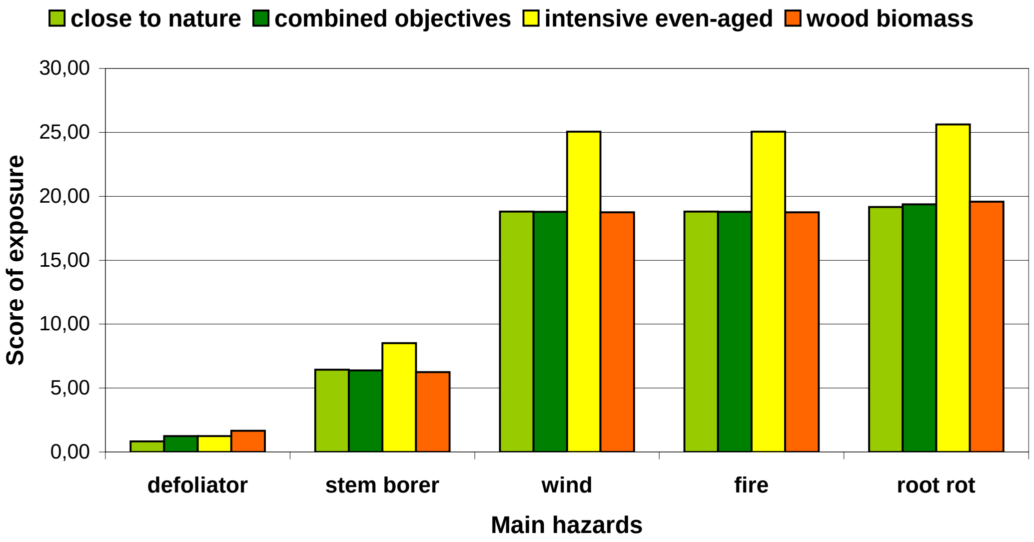



**Figure 5-b** Example of scoring for exposure of *Pinus pinaster* stands to the main hazards in Aquitaine (Uneven impact)

Then we combined susceptibility and exposure (by multiplying the scores) to define stand vulnerability to each hazard.

Finally we quantified hazard occurrence by estimating, using expert knowledge and available inventories data, the average percentage of affected tree per ha during the last 50 years (Table 4). We used their relative importance as weight of vulnerability in the MCRA, i.e. to score risks.

**Table 4** Estimate for main hazard occurrence in the eight case-study regions

| **Case-study region** | **Main hazards - % affected trees/ha/year - relative %** | | | | |
|---|---|---|---|---|---|
| *Aquitaine - Pinus pinaster* | defoliator | stem borer | wind | fire | root rot |
| | 5 | 5 | 0.3 | 0.2 | 0.1 |
| | 47% | 47% | 3% | 2% | 1% |
| *Portugal - Eucalyptus sp.* | leaf rust | leaf beetle | gall insect | fire | stem canker |
| | 10 | 6 | 6 | 1 | 0.2 |
| | 43% | 26% | 26% | 4% | 1% |
| *Baden Wuerttemberg - Picea abies* | root rot | wind | bark beetle | snow | game |
| | 0.9 | 0.3 | 0.3 | 0.02 | 0.01 |
| | 58% | 20% | 20% | 1% | 1% |
| *Austria - Picea abies* | bark beetle | wind | snow | game | sawfly |
| | 0.25 | 0.25 | 0.2 | 0.2 | 0.1 |
| | 25% | 25% | 20% | 20% | 10% |
| *Silesia - Pinus sylvestris* | game | root rot | weevil | sawfly | wind |
| | 1.9 | 0.75 | 0.6 | 0.5 | 0.3 |
| | 47% | 19% | 15% | 12% | 7% |
| *Sweden - Pinus sylvestris* | root rot | weevil | game | bark beetle | wind |
| | 1 | 0.75 | 0.5 | 0.2 | 0.2 |
| | 38% | 28% | 19% | 8% | 8% |
| *Scotland - Pinus sylvestris* | game | wind | weevil | foliar disease | fire |
| | 1.6 | 0.2 | 0.1 | 0.08 | 0.02 |
| | 81% | 9% | 5% | 4% | 1% |
| *Scotland - Picea sitchensis* | game | wind | weevil | aphid | fire |
| | 1.6 | 0.2 | 0.1 | 0.08 | 0.02 |
| | 81% | 9% | 5% | 4% | 1% |

We used Decision Lab® software (2003) to process data. We performed PROMETHEE analyses (Brans et al. 1984, 1986, 2002) to make a complete ranking of the 4 FMAs according to their impact (Phi value) on stand susceptibility, vulnerability and risk considering a combination of the 5 hazards. As preference function we used the V-shape model. As P value we used the maximum, observed value of stand susceptibility or vulnerability in each case-study region. Because the main objective of the study was to find the FMA which reduces at most the risk of damage, we used as decision rule to "minimize" all criteria, i.e. scores of susceptibility or vulnerability to all hazards. We used the Multiple Scenarios Tool to combine risks associated with FMAs in the different case-studies and then provide a pattern of response irrespective of the main tree species and regions.

# 3 Results

3.1. Complete ranking of the four FMAs according to their consequence for stand susceptibility to five main hazards

The stand susceptibility results displayed similar patterns over the eight studied forest types (Figure 6). The stand susceptibility was estimated for a combination of 5 main hazards, it only accounts for the level of damage made by the biotic and abiotic agents. Stand susceptibility is then evaluated irrespective of the consequences of damage for tree growth, quality or mortality.

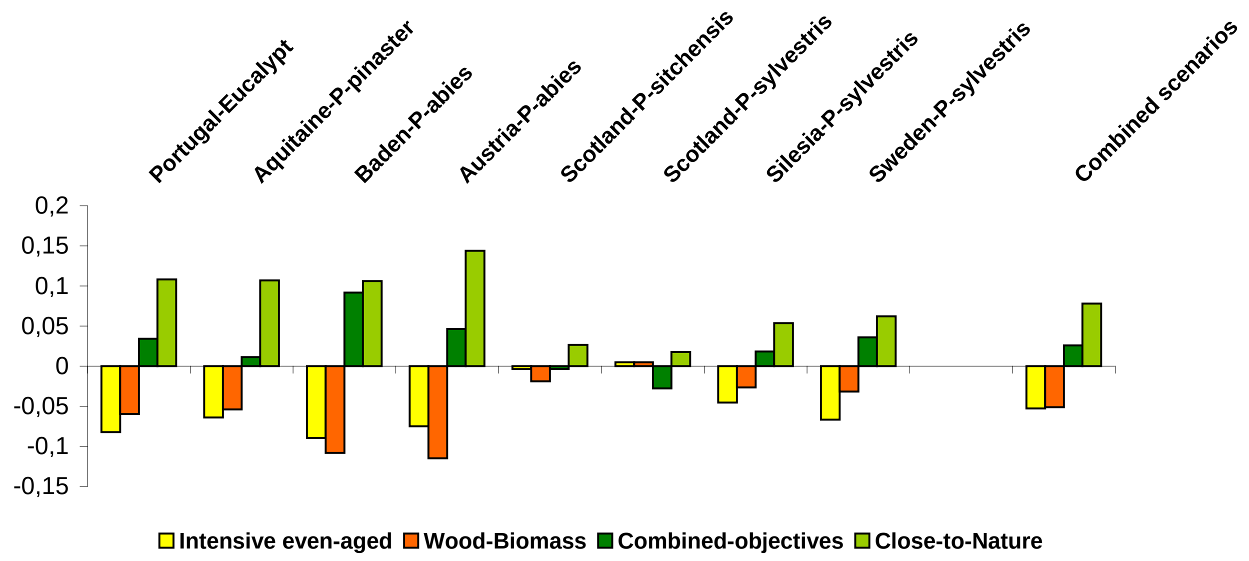



**Figure 6** Ranking of stand susceptibility in regard to forest management option across eight different forest types and for overall results.

It is estimated that less intensive forest management – “close-to-nature” and “combined-objectives” are better ranked in terms of preference for minimizing stand susceptibility. According to this result it is thus predicted that less intensive forest managements may then reduce stand susceptibility to main hazards whereas intensive management, mainly dedicated to wood and biomass production, would aggravate stand susceptibility.
There were no significant differences in susceptibility ranking (Phi values) of the four FMAs between different regions (cases studies) according to a Friedman test ($Q_{obs} = 0.33$, $Q_{crit} = 14.07$, $P = 1$).

Vulnerability

The stand vulnerability combines the level of damage made by biotic and abiotic agents (i.e. stand susceptibility) and their consequences for tree growth, quality or mortality, i.e. the stand exposure to these damage. Again stand vulnerability displayed, in general, similar pattern over the eight studied forest types, yet in these case more differences are observed between forest types (Figure 7).

*Even Impact of damage*

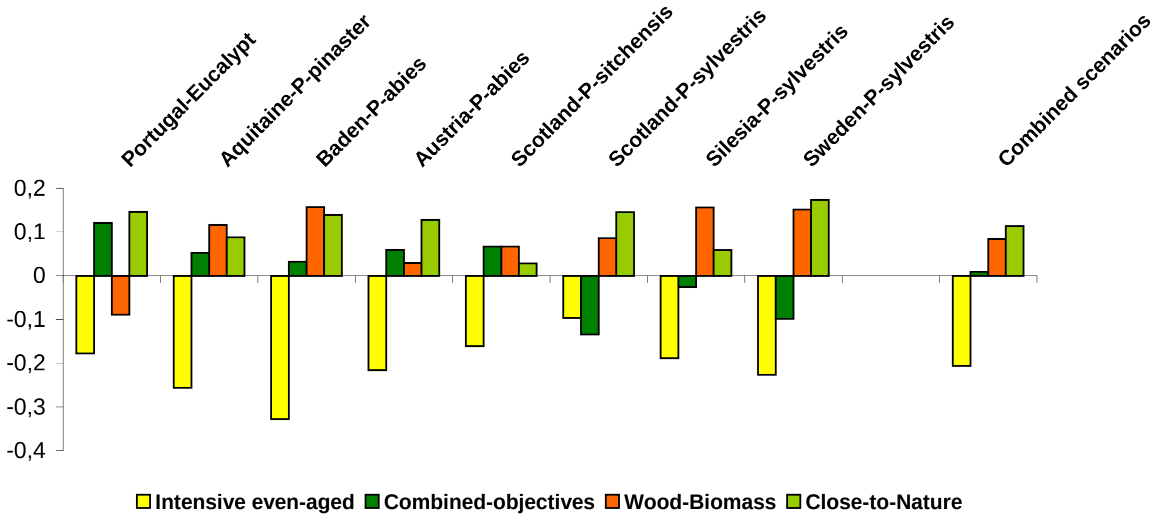



**Figure 7** Ranking of stand vulnerability (susceptibility × exposure) in regard to forest management option across eight different forest types and for overall results, for an even impact of damage.

When using an even ranking of the impact of the three types of damage, there were no significant differences in vulnerability ranking (Phi values) of the four FMAs between the eight different regions (cases studies) according to a Friedman test ($Q_{obs} = 1.33$, $Q_{crit} = 14.07$, $P = 0.99$).
The intensive even-aged management still was the worse for stand vulnerability (susceptibility × exposure) whereas the Wood Biomass production management was as relevant as Close-to-Nature management to reduce vulnerability. This was mainly due to low exposure (low values at stake) of short rotation, biomass-dedicated forests.

*Uneven Impact of damage*

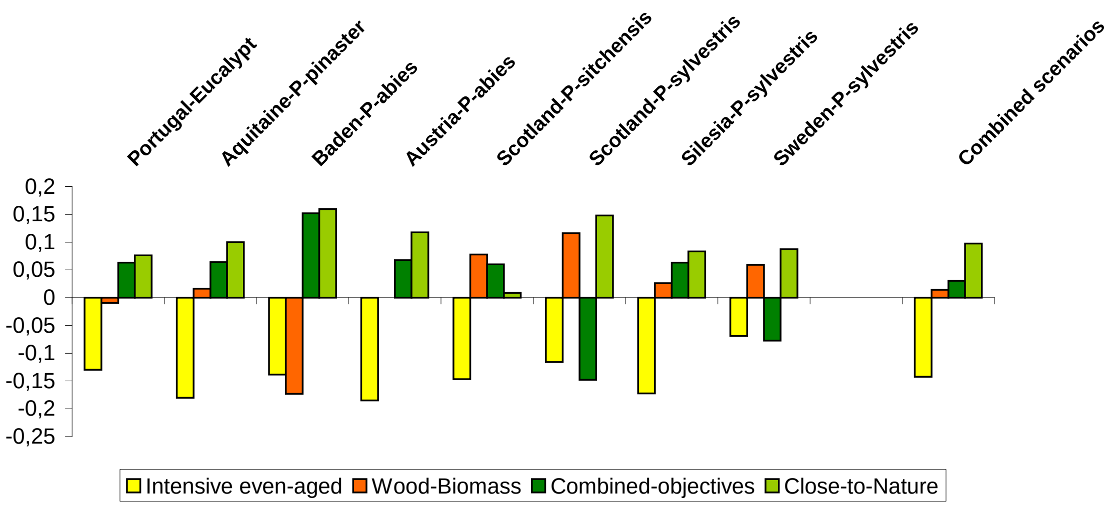



**Figure 8** Ranking of stand vulnerability (susceptibility × exposure) in regard to forest management option across eight different forest types and for overall results, for uneven impact of damage.

When using an uneven ranking of the impact of the three types of damage, there were no significant differences in vulnerability ranking (Phi values) of the four FMAs between the eight different regions (cases studies) according to a Friedman test ($Q_{obs} = 3.13$, $Q_{crit} = 14.07$, $P = 0.87$).

The intensive even-aged management was again the worse for stand vulnerability (susceptibility × exposure) whereas the Wood Biomass production management was as relevant as Combined Objectives management to reduce vulnerability. The Close-to-Nature was the management alternative which reduced at most stand vulnerability. This is probably due to a low exposure (low values at stake) to tree mortality.

<u>Risk</u>

The risk values were obtained by multiplying scores of vulnerability by scores of hazard occurrence.

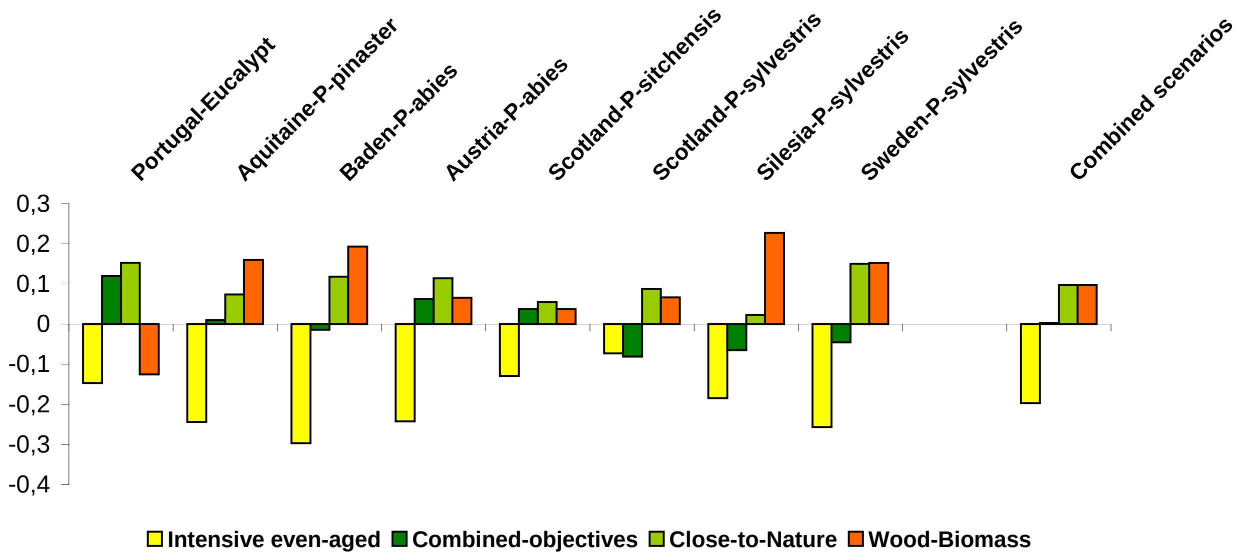



**Figure 9** Ranking of risk at stand level for biotic and abiotic factors in regard to forest management option across eight different forest types and for overall results.

There were no significant differences in risk ranking (Phi values) of the four FMAs between different regions (cases studies) according to a Friedman test ($Q_{obs} = 1.41$, $Q_{crit} = 14.07$, $P = 0.98$).

The ranking of FMAs according to their impact on stand susceptibility, vulnerability and risk of damage was very consistent across the eight regions (no significant differences between Phi values, Friedman tests) indicating that similar FMAs may have similar effects on forest health irrespective of tree species and climate conditions. We could then further combine the eight regions to provide an overview of FMAs rankings.

Overall, the risk of damage seemed lower in intensively managed, short rotation forests, designed to produce wood biomass, mainly because of the reduced stand susceptibility to the most damaging hazards. At the opposite end of the management intensity gradient, close-to-nature systems also induced low overall risk, this time due to lower stand exposure to damage. Intensive even-aged forestry appeared to be subject to the greatest risk, irrespective of tree species and European regions, because it combined higher susceptibility to biotic and abiotic hazards and higher exposure to their impact, in particular to tree mortality and loss of tree growth.

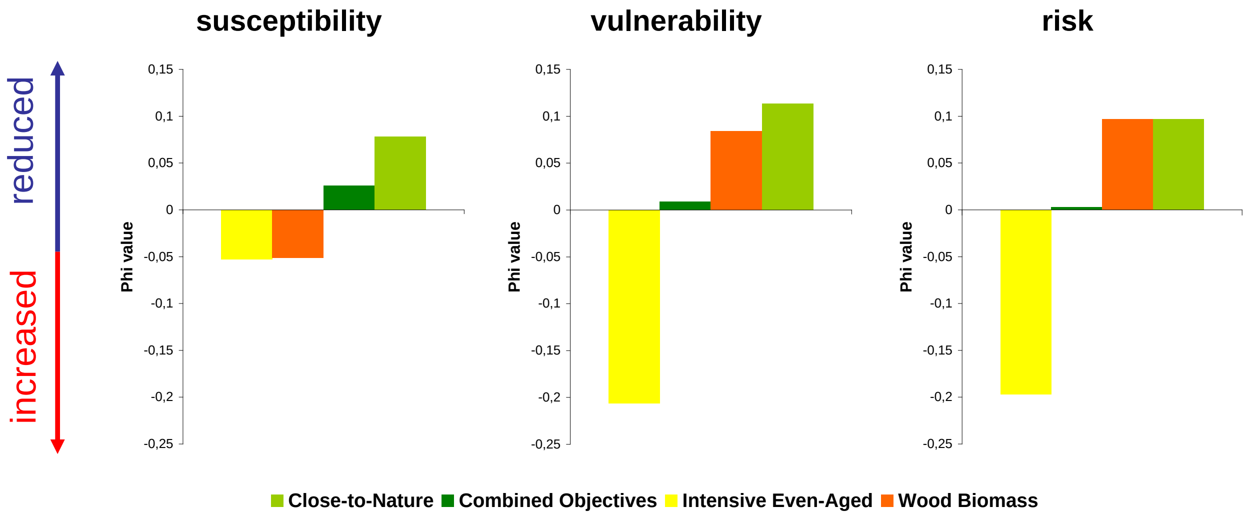



**Figure 10** Overall ranking of stand susceptibility, stand vulnerability and risk for biotic and abiotic factors in regard to forest management option.

## 4 Discussion

Multi-criteria decision analysis models, MCDA, have been widely used in forest planning in regard to several objectives such as biodiversity (Lexer and Seidl 2009), carbon sequestration (Briceno-Elizondo, 2008), watershed management (Sonneveld and Albersen, 1999), wildlife management and conservation (Bock and Salski, 1998; Marcot et al., 2001; Kangas et al., 1993) and landscape attributes (Kangas et al., 2005). In this paper we use Promethee, a method belonging to the class of MCDA (Brans et al., 1984), and adapted it to evaluate the performance of forest management alternative strategies FMAs in several forest types assessing the best sustainable forest management alternatives in regard to overall reduction of forest vulnerability towards disturbances. We propose to call the method as a multi-criteria risk analysis, MCRA, as an innovative approach on forest risk assessment, by considering several risks at the same time and using several criteria under evaluation. At the extent of our knowledge this is the first time that a similar approach is used on forest protection.

Several studies have so far compared the effect of different forest management regimes on stand susceptibility yet regarding the effects of specific damaging agents such as strong winds in spruce stands (Schelhaas 2008), ice in loblolly pine stands (Goodnow et al 2008), bark beetles in Norway spruce forests (Seidl et al. 2009), game (roe deer) in Norway spruce and European larch forests (Vospernik and Reimoser 2008) or statistics of tree mortality (Holecy and Hanewinkel, 2004), using sophisticated damage functions and simulations from tree growth models. However these models are not suitable to integrate several disturbance effects at a time and to run simulations in different, contrasted regions.

The goal of the present contribution is not to analyze and prescribe best forest management solution for a specific problem in a specific region. Instead, our goal is looking for the transferability of patterns and methods by including a large range of hazard factors and various regions in a multi-criteria approach. Uncertainty was addressed through sensitivity analysis by making several runs with different inputs.

The first objective of the study was therefore to test the feasibility of a risk analysis that could combine several risk factors (hazards) and that may apply to a wide range of conditions. We argue that we may have to shift from an optimization-based approach, which provides quantitative outcomes from statistically based modelling but needs accurate inputs and has narrow area of application, to a more comprehensive, though less quantitative, approach that could feed on semi quantitative inputs such as scores and that could be easily implemented in diverse areas. Recently, Linkov et al. (2006) reviewed the use of multi-criteria decision analysis (MCDA) methods to minimize environmental risks and they indicated that they help make structured, logical decisions concerning management options. Multicriteria decision analysis and the PROMETHEE method of ranking was also successfully used to identify optimum tree-harvesting scenarios that would maximise yield while reducing the impact on canopy structure and composition in rain forests (Huth et al. 2005). We followed the same track and tried to design a specific tool, so-called Multi Criteria Risk Analysis, which would allow comparing the effect of different stand management alternatives on the impact of several biotic and abiotic hazards. Using simple assumptions, expert knowledge and matrixes of scores we were able to carry our risk analysis through to a successful conclusion.

The ranking of FMAs according to their effect on stand susceptibility to biotic and abiotic damage clearly distinguished between intensive and extensive regime. The results indicated that the two extreme forest management alternatives — the ‘close to nature alternative’ and the ‘biomass production alternative’ — are the ones providing less vulnerability to forest disturbance, over the middle intensive forest management options. Distinct mechanisms explain the low vulnerability in the two distinct and extreme forest management alternatives. In the short rotation forests, the risk is lower due to reduced susceptibility of stands to the most damaging hazards, which in most cases affect trees at ages older than the rotation time used. At the opposite end, the close-to-nature forest had low overall risk due to lower stand exposure to damage. Intensive even-aged forestry appeared to be subject to the greatest risk, irrespective of tree species and bioclimatic zone. The results were highly consistent over the eight types of European managed forest as no significant differences in relative ranking of four FMAs were detected between forest regions and forest species.

In a recent review on the influences of forest stand management on biotic and abiotic risks of damage, Jactel et al (2009) showed that a reduction in tree species diversity and repeated alteration of canopy structure through thinning and logging operations may lead to higher susceptibility to natural disturbances. These features are less common in close-to-nature forestry that often associates tree species mixture and low impact harvesting, thus explaining part of their lower susceptibility to damaging agents. The method supports systematic preference for close-to-nature forest management in regard to forest susceptibility to disturbances. Multi-functionally managed forests play an important role also in other forest services, namely to maintain biodiversity, which plays by itself an important role within any sustainable forest management framework (Millenium Ecosystem Assessment, 2005). The present findings point out that multi-functionally close-to-nature forests are also less susceptible against disturbances.

The incorporation of stand exposure, to calculate vulnerability, slightly changed the ranking of FMAs. Interesting enough, while the Intensive even-aged management still remained the worst ranked, the short rotation forestry system (Wood biomass) compared well with the extensive alternative in terms of low vulnerability to biotic and abiotic hazards. The main explanation for this change is that the values at stake in short rotation forestry are lower than in intensively managed forests and then less exposed, since the main objective of the former is to produce the maximum of biomass in short time period whatever the wood quality, and also because the economic value of single trees increases with the rotation time, leading to higher loss when a tree dies in an intensively managed forest stand.

We made a sensitivity analysis to test the effect of a different scoring of exposure, giving higher importance to tree mortality ("Uneven impact"), as it may more deeply affect forest managers. The complete ranking of FMAs was very similar, showing that it is unlikely to change with minor changes in exposure estimates.

The use of hazard occurrence to weight the effect of criteria (vulnerability scores) may be viewed as another sensitivity analysis since the comparison between the ranking of vulnerability and risk allow comparing the ranking of vulnerabilities without weights vs. with unequal weights. Once again the relative ranking of FMAs for their effect on risk or vulnerability did not differ substantially. This result support the hypothesis that exposure is one of the main drivers of risk in forests stands. However this may only stand true during equilibrium phase of natural disturbances. When cataclysmic events lead to very high occurrence of some disturbances (storms, large fires, pest outbreaks) then the relative weight of hazard may become less even and can in consequence radically change the ranking of some forest management alternatives. However in such cases, one may also assume that no single forest management can resist to such extended damage.

However this preliminary study has several limitations. First the scoring of damage, susceptibility, exposure, and occurrence of hazards was based on the knowledge of a single panel of expert. Expertise quality is most critical in the use of multi-criteria methods (Kangas and Leskinen, 2005). Although expert judgments may be more or less uncertain and may be widely variable (e.g. Kane, 1995; Wright et al., 1996), in the present work consistent results were found over the five different regions, which is an indication of a consistent, and thus rigorous, assessment. The competence of experts was guaranteed by choosing the highest qualified entomologists and pathologists in each country. Nevertheless, other panels should be solicited to provide different sets of scores that could be compared for their effect on the final ranking.

Second our approach was similar to conditional probabilities, multiplying scores and then cumulating the risk of uncertainty. It does not either take into account the effect of cataclysmic events (e.g. storms) or pest outbreaks that may outweigh some criteria (hazards). In any case we do no expect that cataclysms will affect our results in the sense of changing relative positions of different management options as they possible affect indistinctively all forest management alternatives.

The scope of the study encompassed eight European managed forests and five fast growing tree species. The application of MCRA to a higher number of case-studies, with more contrasted silvicultural regimes and longer living tree species would allow testing the robustness of the method. In depth retrospective analyses, focussing on few well documented case-studies, are still needed to validate the outcomes of the MCRA.

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# Appendix 1

## Scoring the effect of stand management options on relative susceptibility to biotic and abiotic hazards

### Aquitaine – *Pinus pinaster*

| Action | Option | Hazards | | | | |
|---|---|---|---|---|---|---|
| | | Defoliator | Stem borer | wind | fire | Root rot |
| ***Close-to-Nature*** | | | | | | |
| site conditions | sand dune | 1.25 | 0.75 | 0.5 | 0.5 | 0.75 |
| site preparation | harrowing | 1 | 1 | 1 | 0.75 | 1 |
| stand composition | mixed | 0.5 | 0.75 | 1 | 0.75 | 0.5 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural + seeding | 1 | 0.75 | 0.75 | 1.25 | 1 |
| cleaning | mechanical | 1.25 | 1 | 1 | 0.75 | 1 |
| thinning-pruning | selective | 1 | 1 | 1.25 | 1.25 | 1.25 |
| harvesting | shelterwood > 80 years | 1.25 | 1 | 1.25 | 1.25 | 1.25 |
| ***Combined objectives*** | | | | | | |
| site conditions | sand dunes | 1.25 | 0.75 | 0.5 | 0.5 | 0.75 |
| site preparation | strip ploughing, harrowing, low fertilization, weed control | 1 | 1.25 | 1 | 0.5 | 1 |
| stand composition | pure - even-aged | 1.5 | 1.25 | 1 | 1.25 | 1.5 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | seeding + planting | 1 | 1.25 | 1.25 | 0.75 | 1 |
| cleaning | mechanical, before each thinning | 1.25 | 1.25 | 1 | 0.5 | 1 |
| thinning-pruning | 3-4 thinnings, removing 30% of trees, pruning | 1 | 1.5 | 1.5 | 0.75 | 1.5 |
| harvesting | clear cut at 80 years | 1.25 | 1 | 1.25 | 0.75 | 1.5 |
| ***Intensive even-aged*** | | | | | | |
| site conditions | mesophylous podzols | 0.75 | 1.25 | 1.25 | 1.25 | 1 |
| site preparation | full ploughing, harrowing, drainage, cleaning, fertilization P60, chemical weed control | 1 | 1.5 | 0.75 | 0.5 | 1.25 |
| stand composition | pure, even-aged | 1.5 | 1.25 | 1 | 1.25 | 1.5 |
| genetic material | improved varieties | 1 | 1.25 | 1.25 | 1 | 1 |
| regeneration type | planting 1250t/ha | 1 | 1.5 | 1.5 | 0.75 | 1 |
| cleaning | mechanical, or chemical, before thinnings | 1.25 | 1.25 | 1 | 0.5 | 1 |
| thinning-pruning | pruning, 3-4 thinnings, removing 33% of trees | 1 | 1.5 | 1.5 | 0.5 | 1.5 |
| harvesting | clear cut at 45 years | 1.5 | 1 | 1.5 | 0.5 | 1.5 |
| ***Wood biomass*** | | | | | | |
| site conditions | most fertile | 1 | 1.5 | 0.75 | 1.25 | 1 |
| site preparation | full ploughing, harrowing, drainage, cleaning, fertilization P80, weed control | 1 | 1.5 | 1.25 | 0.5 | 1.25 |
| stand composition | pure, even-aged | 1.5 | 1.25 | 1 | 1.25 | 1.5 |
| genetic material | improved varieties | 1 | 1.25 | 1.25 | 1 | 1 |
| regeneration type | planting 2500t/ha | 1 | 0.75 | 0.75 | 1.25 | 1.25 |
| cleaning | mechanical, chemical | 1.25 | 1.25 | 1 | 0.5 | 1 |
| thinning-pruning | 1-2 heavy thinnings | 1 | 1.25 | 1.5 | 0.75 | 1.25 |
| harvesting | clear cut at 15-30 years | 1.5 | 1 | 1.5 | 0.5 | 1.5 |

Portugal – *Eucalyptus sp.*

| **Action** | **Option** | **Hazards** | | | | |
|---|---|---|---|---|---|---|
| ***Close-to-Nature*** | | **Leaf beetle** | **Gall insect** | **Leaf rust** | **Stem canker** | **Fire** |
| site conditions | Atlantic climate, elevation < 450m | 1 | 1,25 | 1,25 | 0,75 | 1 |
| site preparation | Stump destruction and harrowing for woody debris | 1 | 1 | 1 | 0,75 | 1 |
| stand composition | mixed | 0,75 | 0,5 | 0,5 | 0,5 | 0,5 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural | 0,75 | 0,75 | 0,75 | 0,75 | 0,75 |
| cleaning | Ocasionally; mechanical | 1 | 0,75 | 0,75 | 1 | 1,25 |
| thinning-pruning | Selective | 0,75 | 0,75 | 0,75 | 0,75 | 0,75 |
| harvesting | shelterwood >15 years | 1 | 0,75 | 0,75 | 1,25 | 1 |
| ***Combined objectives*** | | | | | | |
| site conditions | Atlantic climate, elevation < 450m | 1 | 1,25 | 1,25 | 0,75 | 1 |
| site preparation | previously been there and/or ripping. | 1 | 1 | 1 | 0,75 | 1 |
| stand composition | mixed even-aged or uneven | 1 | 0,75 | 0,75 | 0,75 | 0,5 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | To favour the conversion to mixed stands | 1 | 0,75 | 0,75 | 0,75 | 0,75 |
| cleaning | mixed stand | 1 | 0,75 | 0,75 | 1 | 1,25 |
| thinning-pruning | mixed stand | 1 | 1 | 0,75 | 1 | 0,75 |
| harvesting | clear cut at 12 years | 1,25 | 1,25 | 1 | 1 | 0,75 |
| ***Intensive even-aged*** | | | | | | |
| site conditions | Atlantic climate, elevation < 450m | 1 | 1,25 | 1,25 | 0,75 | 1 |
| site preparation | previously been there and/or ripping. Fertilization at planting: 30g/plant of NPK slow release fertilizer + 175g/plant of a phosphorus fertilizer. Mechanical fertilization with NPK fertilizer at year 2. | 0,75 | 1,25 | 0,75 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1,5 | 1,25 | 1,25 | 1,25 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting to replace dead trees (15%) | 1,25 | 1,25 | 1 | 1 | 1 |
| cleaning | time in a single operation) | 1 | 1 | 1 | 0,75 | 0,75 |
| thinning-pruning | Botrytis cinerea attacks | 1 | 1 | 0,75 | 0,75 | 0,75 |
| harvesting | Cuttings are performed in order to minimize the visual/ecological effects of clear-felling | 1,25 | 1,25 | 1,25 | 1 | 1 |
| ***Wood biomass*** | | | | | | |
| site conditions | Atlantic climate, elevation < 450m | 1 | 1,25 | 1,25 | 0,75 | 1 |
| site preparation | previously been there and/or ripping. Fertilization: 30g/plant of NPK slow release fertilizer + 175g/plant of a phosphorus fertilizer. Mechanical fertilization with NPK fertilizer at year 1 | 0,75 | 1,25 | 0,75 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1,5 | 1,25 | 1,25 | 1,25 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | Planting: spacing of 0.3 m x 0.9 m (final density ~37000 trees/ha) | 1,25 | 1,25 | 1 | 1 | 1,25 |
| cleaning | no | 1 | 0,75 | 0,75 | 1 | 1,25 |
| thinning-pruning | no | 1 | 1 | 1 | 1 | 1,25 |
| harvesting | clear cut at 5 years | 0,75 | 0,75 | 1 | 0,5 | 0,5 |

Baden Wurttemberg – *Picea abies*

| Action | Option | Hazards | | | | |
|---|---|---|---|---|---|---|
| ***Close-to-Nature*** | | **Bark beetle** | **Root rot** | **Wind** | **Snow** | **Game** |
| site conditions | adequate sites | 0,5 | 0,5 | 0,5 | 1 | 1 |
| site preparation | no | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed | 0,5 | 1 | 1,25 | 1 | 0,5 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural | 0,75 | 0,75 | 0,75 | 1 | 0,5 |
| cleaning | mechanical weed control | 1,25 | 1 | 1 | 1 | 0,5 |
| thinning-pruning | 4 thinnings with 80m3 max | 0,75 | 0,75 | 0,75 | 0,75 | 1 |
| harvesting | target diameter harvest <120 years | 0,75 | 1,25 | 1 | 1,25 | 1 |
| ***Combined objectives*** | | | | | | |
| site conditions | adequate sites | 0,5 | 0,5 | 0,5 | 1 | 1 |
| site preparation | no | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed | 0,5 | 1 | 1,25 | 1 | 1,25 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural | 0,75 | 0,75 | 0,75 | 1 | 0,75 |
| cleaning | mechenical weed control | 1 | 1 | 1 | 1 | 0,5 |
| thinning-pruning | 3 - 4 thinnings with 80m3 max | 0,75 | 0,75 | 0,75 | 0,5 | 0,75 |
| harvesting | target diameter harvest 120 - 140 years | 0,75 | 1,25 | 1 | 1,25 | 1,25 |
| ***Intensive even-aged*** | | | | | | |
| site conditions | various sites from adequate to less adequate | 1,25 | 1,25 | 0,5 | 1 | 1 |
| site preparation | liming | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed less than 20% | 1,5 | 0,75 | 1 | 1 | 1,5 |
| genetic material | genetically improved | 1,25 | 1,25 | 1 | 1 | 1 |
| regeneration type | planting 2 x 3m | 1 | 1 | 1 | 1 | 1,25 |
| cleaning | mechenical weed control | 1,25 | 1 | 1 | 1 | 1,5 |
| thinning-pruning | 3 - 4 thinnings with 80m3 max | 1,25 | 0,75 | 1 | 1,25 | 1 |
| harvesting | clear cut (<0.5ha); 70 -110 years | 1 | 0,75 | 1 | 1,25 | 1,5 |
| ***Wood biomass*** | | | | | | |
| site conditions | all sites | 1,25 | 1,25 | 0,5 | 1 | 1 |
| site preparation | liming & fertilization | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed less than 20% | 1,5 | 0,75 | 1 | 1 | 1,5 |
| genetic material | genetically improved | 1,25 | 1,25 | 1 | 1 | 1 |
| regeneration type | planting 2 x 3m | 1 | 1 | 1 | 1 | 1,5 |
| cleaning | mechenical weed control | 1,25 | 1 | 1 | 1 | 1,5 |
| thinning-pruning | 2 thinning;  80m3 | 1,25 | 0,75 | 1,25 | 1,25 | 1,25 |
| harvesting | clear cut (<0.5ha); 50 - 80 years | 1 | 0,75 | 1 | 1,25 | 1,5 |

## Austria – *Picea abies*

| Action | Option | Hazards | | | | |
|---|---|---|---|---|---|---|
| ***Close-to-Nature*** | | **Brak beetle** | **Sawfly** | **Game** | **Wind** | **Snow** |
| site conditions | Mountainous areas | 1 | 0,5 | 1 | 1 | 1,25 |
| site preparation | no | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed spruce forest, uneven-aged | 0,75 | 0,75 | 0,75 | 0,5 | 1 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural | 1 | 1 | 0,5 | 1 | 1 |
| cleaning | no | 1 | 0,5 | 0,5 | 1 | 1 |
| thinning-pruning | selective | 0,75 | 1,25 | 1 | 1 | 1 |
| harvesting | selective | 1 | 1 | 1 | 1,25 | 1,25 |
| ***Combined objectives*** | | | | | | |
| site conditions | Mountainous and low mountain range stands | 1,25 | 1 | 1 | 1 | 1,5 |
| site preparation | no | 1 | 1 | 1 | 1 | 1 |
| stand composition | pure - uneven-aged | 1,25 | 1,25 | 1,25 | 1,25 | 1,25 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting and natural | 1 | 1,25 | 1 | 1 | 1 |
| cleaning | slash removal, no weed control | 0,75 | 0,75 | 0,5 | 1 | 1 |
| thinning-pruning | several moderate thinning operations in the course of the rotation period | 0,75 | 1 | 0,75 | 0,75 | 0,75 |
| harvesting | strip and femel system | 1,25 | 1,25 | 1,25 | 1,25 | 1,25 |
| ***Intensive even-aged*** | | | | | | |
| site conditions | lowland and low mountain range stands | 1,5 | 1,25 | 1 | 1,5 | 1 |
| site preparation | no | 1 | 1 | 1 | 1 | 1 |
| stand composition | pure, even-aged | 1,5 | 1,5 | 1,5 | 1,5 | 1,5 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting (and natural) | 1 | 1,25 | 1,25 | 1 | 1 |
| cleaning | slash removal, weed control | 0,75 | 1,5 | 1,5 | 1 | 1 |
| thinning-pruning | several moderate thinning operations in the course of the rotation period | 0,75 | 1 | 1 | 0,75 | 0,75 |
| harvesting | clear cut at 80 years (max. area 2ha) | 1,5 | 1,25 | 1,5 | 1,5 | 1,25 |
| ***Wood biomass*** | | | | | | |
| site conditions | lowland stands | 1,5 | 1,5 | 1 | 1,5 | 1 |
| site preparation | fertilization, weed control | 1,25 | 1,25 | 1 | 1 | 1,25 |
| stand composition | pure, even-aged | 1,5 | 1,5 | 1,5 | 1,5 | 1,5 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting | 1 | 1,25 | 1,5 | 1 | 1 |
| cleaning | slash removal, weed control | 0,75 | 1,5 | 1,5 | 1 | 1 |
| thinning-pruning | 1-2 heavy thinnings | 1,25 | 1,25 | 1,25 | 1,25 | 0,5 |
| harvesting | clear cut at 40 years | 0,5 | 1,5 | 1,5 | 1,5 | 1,25 |

Silesia – *Pinus sylvestris*

| Action | Option | Hazards | | | | |
|---|---|---|---|---|---|---|
| ***Close-to-Nature*** | | **Sawfly** | **Weevil** | **Root rot** | **Game** | **Wind** |
| site conditions | above medium | 0,75 | 0,75 | 1,25 | 0,75 | 1,25 |
| site preparation | no | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed | 1 | 1 | 1 | 1 | 1 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural + planting | 1 | 0,75 | 0,75 | 0,5 | 0,75 |
| cleaning | 1-2 times | 1 | 1 | 1 | 1 | 1 |
| thinning-pruning | selective, 1-2 times | 1 | 1 | 0,75 | 1 | 1 |
| harvesting | clearcut > 100 years | 1 | 1 | 1 | 1 | 1,25 |
| ***Combined objectives*** | | | | | | |
| site conditions | adequate for Scots pine | 1 | 1 | 1 | 1 | 1 |
| site preparation | no | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed | 1 | 1 | 1 | 1 | 1 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting | 1 | 1 | 1 | 1 | 1 |
| cleaning | 1-2 times | 1 | 1 | 1 | 1 | 1 |
| thinning-pruning | 1-2 selective thinning in both medium and adult phase | 1 | 1 | 0,75 | 1 | 1 |
| harvesting | clear cut at >100 years, limit 2 ha | 1 | 1 | 1 | 1 | 1 |
| ***Intensive even-aged*** | | | | | | |
| site conditions | adequate for Scots pine | 1 | 1 | 1 | 1 | 1 |
| site preparation | no | 1 | 1 | 1 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1,25 | 1,25 | 1,25 | 1,25 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting 8-10 thous./ha | 1 | 1 | 1 | 1 | 1 |
| cleaning | 1-2 times | 1 | 1 | 1 | 1 | 1 |
| thinning-pruning | 1-2 selective thinning in both medium and adult phase | 1 | 1 | 0,75 | 1 | 1 |
| harvesting | clear cut at 90-100 years, limit 6 ha | 1 | 1,25 | 1,25 | 1,25 | 1,25 |
| ***Wood biomass*** | | | | | | |
| site conditions | fertile | 0,75 | 0,75 | 1,25 | 0,75 | 1,25 |
| site preparation | Mechanical, physical and chemical | 0,75 | 0,75 | 1,25 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1,25 | 1,25 | 1,25 | 1,25 |
| genetic material | improved varieties | 0,75 | 0,75 | 0,75 | 1 | 0,75 |
| regeneration type | planting 8-10 thous./ha | 1 | 1 | 1 | 1 | 1 |
| cleaning | schematic reduction | 1 | 1 | 1 | 1 | 1 |
| thinning-pruning | schematic reduction | 1 | 1 | 1,25 | 1 | 1,25 |
| harvesting | clear cut at 50-60 years, no area limit | 0,75 | 1,5 | 1,25 | 1,25 | 1,25 |

## Sweden – *Pinus sylvestris*

| Action | Option | Hazards | | | | |
|---|---|---|---|---|---|---|
| ***Close-to-Nature*** | | **Weevil** | **Bark beetle** | **Root rot** | **Game** | **Wind** |
| site conditions | average | 0,75 | 0,75 | 1,25 | 0,75 | 0,75 |
| site preparation | no | 1,25 | 1 | 0,75 | 1 | 1 |
| stand composition | pine-dominated | 0,5 | 0,75 | 1 | 1 | 0,75 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural + planting | 0,75 | 1 | 1 | 1 | 0,75 |
| cleaning | once | 1 | 1 | 1,25 | 1,25 | 0,75 |
| thinning-pruning | selective, 1-2 times | 1 | 1,25 | 1,25 | 1 | 1,25 |
| harvesting | clearcut > 100 years | 1,5 | 1,25 | 1,25 | 1 | 1,25 |
| ***Combined objectives*** | | | | | | |
| site conditions | adequate for Scots pine | 1 | 1 | 0,75 | 1 | 0,75 |
| site preparation | soil scarification | 1,25 | 1 | 0,75 | 1 | 1 |
| stand composition | pine-dominated | 0,5 | 0,75 | 0,75 | 0,75 | 0,75 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting | 1 | 1 | 1,25 | 1,25 | 1,25 |
| cleaning | once | 1 | 1 | 1,25 | 1,25 | 1 |
| thinning-pruning | 1-2 selective thinnings, no pruning | 1 | 1,25 | 1,25 | 1 | 1,25 |
| harvesting | clear-cut at >100 years, < 5 ha in size | 1,25 | 1,25 | 1,25 | 1 | 1,25 |
| ***Intensive even-aged*** | | | | | | |
| site conditions | adequate for Scots pine | 1 | 1 | 0,75 | 1 | 1 |
| site preparation | soil scarification | 1,25 | 1 | 0,75 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1,25 | 1,25 | 1,25 | 1,25 |
| genetic material | selected seed sources | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting 2500 per ha | 1,5 | 1 | 1,25 | 1,25 | 1 |
| cleaning | once | 1 | 1,25 | 1,25 | 1,25 | 0,75 |
| thinning-pruning | 1-2 selective thinning in both medium and adult phase | 1 | 1,25 | 1,25 | 1 | 1,25 |
| harvesting | clear-cut at ca 100 years, > 5 ha | 1,5 | 1,5 | 1,25 | 1 | 1,25 |
| ***Wood biomass*** | | | | | | |
| site conditions | above average | 0,75 | 0,75 | 1,25 | 0,75 | 0,75 |
| site preparation | soil scarification | 0,5 | 1 | 1,25 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1,25 | 1,25 | 1,25 | 1,25 |
| genetic material | selected seed sources | 1 | 1 | 1 | 1 | 0,75 |
| regeneration type | planting 2500 per ha | 1,5 | 1 | 1,25 | 1,25 | 1,25 |
| cleaning | no | 1 | 1 | 1,25 | 1 | 1 |
| thinning-pruning | one thinning, no pruning | 1 | 1,25 | 1,25 | 1 | 1,25 |
| harvesting | clear clear-cut at 60-80 years, no area limit | 1,5 | 1,25 | 1,25 | 1 | 1,25 |

## Scotland – *Pinus sylvestris*

| Action | Option | Hazards | | | | |
|---|---|---|---|---|---|---|
| ***Close-to-Nature*** | | **Foliar disease** | **Weevil** | **Game** | **Wind** | **Fire** |
| site conditions | podzol | 1 | 1 | 1 | 1 | 1 |
| site preparation | none | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed | 1 | 0,75 | 1 | 1 | 0,75 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural | 1 | 1 | 1 | 1 | 0,5 |
| cleaning | mechanical | 1 | 1 | 0,75 | 1 | 1 |
| thinning-pruning | selective | 1 | 1 | 1 | 1 | 1 |
| harvesting | shelterwood > 80 years | 1 | 1 | 1 | 1 | 1 |
| ***Combined objectives*** | | | | | | |
| site conditions | forest brown earths | 1 | 1 | 1 | 1 | 1 |
| site preparation | mounding / scarifying | 1 | 0,75 | 1 | 1 | 1 |
| stand composition | pure - even-aged | 1,25 | 1 | 0,75 | 1,25 | 1 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting 2500t/ha | 0,75 | 1,25 | 1,25 | 1,25 | 1 |
| cleaning | none | 1,5 | 1 | 1 | 1 | 1,25 |
| thinning-pruning | 3-4 thinnings, removing 30% of trees, pruning | 0,5 | 1 | 1 | 1,5 | 0,5 |
| harvesting | clear cut at 80 years | 0,75 | 1,5 | 1,25 | 0,5 | 0,5 |
| ***Intensive even-aged*** | | | | | | |
| site conditions | forest brown earths | 1 | 1 | 1 | 1 | 1 |
| site preparation | mounding / scarifying | 1 | 0,75 | 1 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1 | 0,75 | 1,25 | 1 |
| genetic material | improved varieties | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting 1250t/ha | 0,75 | 1,25 | 1,25 | 1,25 | 1 |
| cleaning | mechanical, or chemical, before thinnings | 0,5 | 1 | 1 | 1 | 1,25 |
| thinning-pruning | pruning, 3-4 thinnings, removing 33% of trees | 0,5 | 1 | 1 | 1,5 | 0,5 |
| harvesting | clear cut at 45 years | 0,75 | 1,5 | 1,25 | 0,5 | 0,5 |
| ***Wood biomass*** | | | | | | |
| site conditions | podzol | 1 | 1 | 1 | 1 | 1 |
| site preparation | mounding / scarifying | 1 | 0,75 | 1 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1 | 0,75 | 1,25 | 1 |
| genetic material | improved varieties | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting 2500t/ha | 0,75 | 1,25 | 1,25 | 1,25 | 1 |
| cleaning | mechanical, chemical | 0,5 | 1 | 1 | 1 | 1,25 |
| thinning-pruning | 1-2 heavy thinnings | 0,5 | 1 | 1 | 1,5 | 0,5 |
| harvesting | clear cut at 15-30 years | 0,75 | 1,5 | 1,25 | 0,5 | 0,5 |

## Scotland – *Picea sitchensis*

| Action | Option | Hazards | | | | |
|---|---|---|---|---|---|---|
| ***Close-to-Nature*** | | **Aphid** | **Weevil** | **Game** | **Wind** | **Fire** |
| site conditions | forest brown earths | 1 | 1 | 1 | 1 | 1 |
| site preparation | none | 1 | 1 | 1 | 1 | 1 |
| stand composition | mixed | 1 | 0,75 | 1 | 1 | 0,75 |
| genetic material | no | 1 | 1 | 1 | 1 | 1 |
| regeneration type | natural | 1 | 1 | 1 | 1 | 1 |
| cleaning | mechanical | 1 | 1 | 1 | 0,75 | 1 |
| thinning-pruning | selective | 1 | 0,75 | 1 | 1 | 0,75 |
| harvesting | shelterwood > 80 years | 1 | 1 | 1 | 1 | 1 |
| ***Combined objectives*** | | | | | | |
| site conditions | gleyed mineral soil | 1 | 1 | 1 | 1 | 1 |
| site preparation | mounding / scarifying | 1 | 0,75 | 1 | 1 | 1 |
| stand composition | pure - even-aged | 1,25 | 1 | 0,75 | 1,25 | 1 |
| genetic material | improved varieties | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting 2500t/ha | 1 | 1,25 | 1,25 | 1 | 1 |
| cleaning | none | 1 | 1 | 1 | 1 | 1 |
| thinning-pruning | 3-4 thinnings, removing 30% of trees | 1 | 1 | 1 | 1,5 | 0,5 |
| harvesting | clear cut at 45-55 years | 0,5 | 1,5 | 1,25 | 0,5 | 0,5 |
| ***Intensive even-aged*** | | | | | | |
| site conditions | forest brown earths | 1 | 1 | 1 | 1 | 1 |
| site preparation | mounding / scarifying | 1 | 0,75 | 1 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1 | 0,75 | 1,25 | 1 |
| genetic material | improved varieties | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting 2500t/ha | 1 | 1,25 | 1,25 | 1 | 1 |
| cleaning | none | 1 | 1 | 1 | 1 | 1 |
| thinning-pruning | 3-4 thinnings, removing 33% of trees | 1 | 1 | 1 | 1,5 | 0,5 |
| harvesting | clear cut at 45-65 years | 0,5 | 1,5 | 1,25 | 0,5 | 0,5 |
| ***Wood biomass*** | | | | | | |
| site conditions | gleyed mineral soil | 1 | 1 | 1 | 1 | 1 |
| site preparation | scarifying | 1 | 0,75 | 1 | 1 | 1 |
| stand composition | pure, even-aged | 1,25 | 1 | 0,75 | 1,25 | 1 |
| genetic material | improved varieties | 1 | 1 | 1 | 1 | 1 |
| regeneration type | planting 3000t/ha | 1 | 1,25 | 1,25 | 1 | 1 |
| cleaning | none | 1 | 1 | 1 | 1 | 1 |
| thinning-pruning | none | 1 | 1 | 1 | 1,5 | 1 |
| harvesting | clear cut at 15-30 years | 0,5 | 1,5 | 1,25 | 0,5 | 0,5 |

# Appendix 2

**Score of importance for three types of damage** (loss in wood quality, loss in tree growth, tree mortality) in each case-study region and Forest Management Alternative, using a five levels scale: 0, 0.25, 0.50, 0.75, and 1 for null, low, moderate, high and very high respectively.

***Aquitaine - Pinus pinaster***

| | close to nature | combined objectives | intensive even-aged | wood biomass |
|---|---|---|---|---|
| **wood quality** | 0.75 | 0.5 | 0.75 | 0 |
| **growth loss** | 0.5 | 0.75 | 0.75 | 1 |
| **tree mortality** | 0.75 | 0.75 | 1 | 0.75 |

***Portugal - Eucalyptus sp.***

| | close to nature | combined objectives | intensive even-aged | wood biomass |
|---|---|---|---|---|
| **wood quality** | 0.25 | 0.25 | 0.25 | 0 |
| **growth loss** | 0.75 | 0.75 | 1 | 1 |
| **tree mortality** | 0.75 | 0.75 | 1 | 0.75 |

***Baden Wurttemberg - Picea abies***

| | close to nature | combined objectives | intensive even-aged | wood biomass |
|---|---|---|---|---|
| **wood quality** | 0.5 | 0.75 | 1 | 0 |
| **growth loss** | 0.5 | 0.75 | 0.75 | 1 |
| **tree mortality** | 0.75 | 0.75 | 1 | 1 |

***Austria - Picea abies***

| | close to nature | combined objectives | intensive even-aged | wood biomass |
|---|---|---|---|---|
| **wood quality** | 0.75 | 0.5 | 0.75 | 0 |
| **growth loss** | 0.5 | 0.75 | 0.75 | 1 |
| **tree mortality** | 0.75 | 0.75 | 1 | 0.75 |

***Silesia - Pinus sylvestris***

| | close to nature | combined objectives | intensive even-aged | wood biomass |
|---|---|---|---|---|
| **wood quality** | 0.75 | 0.75 | 0.75 | 0 |
| **growth loss** | 0.5 | 1 | 1 | 1 |
| **tree mortality** | 0.75 | 0.75 | 1 | 0.75 |

***Sweden - Pinus sylvestris***

| | close to nature | combined objectives | intensive even-aged | wood biomass |
|---|---|---|---|---|
| **wood quality** | 0.75 | 0.75 | 0.75 | 0 |
| **growth loss** | 0.5 | 1 | 1 | 1 |
| **tree mortality** | 0.75 | 0.75 | 1 | 0.75 |

***Scotland - Pinus sylvestris***

| | close to nature | combined objectives | intensive even-aged | wood biomass |
|---|---|---|---|---|
| **wood quality** | 0.75 | 0.75 | 0.75 | 0.25 |
| **growth loss** | 0.5 | 0.75 | 0.75 | 1 |
| **tree mortality** | 0.75 | 1 | 1 | 0.75 |

***Scotland - Picea sitchensis***

| | close to nature | combined objectives | intensive even-aged | wood biomass |
|---|---|---|---|---|
| **wood quality** | 0.75 | 0.5 | 0.75 | 0.25 |
| **growth loss** | 0.5 | 0.75 | 0.75 | 1 |
| **tree mortality** | 0.75 | 0.75 | 1 | 0.75 |

# Appendix 3

**Score of contribution of main hazards to three types of damage** (loss in wood quality, loss in tree growth, tree mortality) in each case-study region and Forest Management Alternative, using a five levels scale: 0, 0.25, 0.50, 0.75, and 1 for null, low, moderate, high and very high respectively.

### *Aquitaine - Pinus pinaster*

| | defoliator | stem borer | wind | fire | root rot |
|---|---|---|---|---|---|
| **wood quality** | 0 | 0.75 | 0.25 | 0.25 | 0 |
| **growth loss** | 0.5 | 0 | 0 | 0 | 0.25 |
| **tree mortality** | 0 | 0.25 | 0.75 | 0.75 | 0.75 |

### *Portugal - Eucalyptus sp.*

| | leaf rust | leaf beetle | gall insect | fire | stem canker |
|---|---|---|---|---|---|
| **wood quality** | 0 | 0 | 0 | 0.5 | 0.25 |
| **growth loss** | 0.5 | 1 | 0.75 | 0.25 | 0.25 |
| **tree mortality** | 0 | 0.25 | 0 | 0.75 | 0.5 |

### *Baden Wurttemberg - Picea abies*

| | root rot | wind | bark beetle | snow | game |
|---|---|---|---|---|---|
| **wood quality** | 0.75 | 0.75 | 0.5 | 0.75 | 0.75 |
| **growth loss** | 0 | 0.25 | 0.25 | 0.25 | 0.25 |
| **tree mortality** | 0.25 | 0.75 | 0.5 | 0.75 | 0.25 |

### *Austria - Picea abies*

| | bark beetle | wind | snow | game | sawfly |
|---|---|---|---|---|---|
| **wood quality** | 0.5 | 0.25 | 0.25 | 0.75 | 0 |
| **growth loss** | 0 | 0.25 | 0.75 | 0.25 | 0.75 |
| **tree mortality** | 1 | 1 | 1 | 0.25 | 0 |

### *Silesia - Pinus sylvestris*

| | Game | root rot | weevil | sawfly | wind |
|---|---|---|---|---|---|
| **wood quality** | 0.5 | 0.5 | 0 | 0 | 0.25 |
| **growth loss** | 0 | 0.25 | 0 | 0.25 | 0 |
| **tree mortality** | 0.25 | 0.5 | 0.75 | 0 | 0.75 |

### *Sweden - Pinus sylvestris*

| | root rot | weevil | game | bark beetle | wind |
|---|---|---|---|---|---|
| **wood quality** | 0.5 | 0 | 0.5 | 0 | 0.25 |
| **growth loss** | 0.25 | 0 | 0.25 | 0 | 0 |
| **tree mortality** | 0.5 | 0.5 | 0.25 | 0.75 | 0.75 |

### *Scotland - Pinus sylvestris*

| | game | wind | weevil | foliar disease | fire |
|---|---|---|---|---|---|
| **wood quality** | 0.5 | 0.5 | 0 | 0.25 | 0.75 |
| **growth loss** | 0.5 | 0.25 | 0.75 | 1 | 0.25 |
| **tree mortality** | 0.25 | 1 | 1 | 1 | 1 |

### *Scotland - Picea sitchensis*

| | game | wind | weevil | aphid | fire |
|---|---|---|---|---|---|
| **wood quality** | 0.5 | 0.5 | 0 | 0.5 | 0.75 |
| **growth loss** | 0.5 | 0.25 | 0.75 | 0.75 | 0.25 |
| **tree mortality** | 0.25 | 1 | 1 | 0.75 | 1 |

# Appendix 4

**Score of stand exposure to main hazards** according to Forest Management Alternative in each case-study region – *even impact of damage*

***Aquitaine - Pinus pinaster***

| | defoliator | stem borer | wind | fire | root rot |
|---|---|---|---|---|---|
| **close to nature** | 0,083 | 0,250 | 0,250 | 0,250 | 0,229 |
| **combined objectives** | 0,125 | 0,188 | 0,229 | 0,229 | 0,250 |
| **intensive even-aged** | 0,125 | 0,271 | 0,313 | 0,313 | 0,313 |
| **wood biomass** | 0,167 | 0,063 | 0,188 | 0,188 | 0,271 |

***Portugal - Eucalyptus sp.***

| | leaf rust | leaf beetle | gall insect | fire | stem canker |
|---|---|---|---|---|---|
| **close to nature** | 0,125 | 0,313 | 0,188 | 0,292 | 0,208 |
| **combined objectives** | 0,125 | 0,313 | 0,188 | 0,292 | 0,208 |
| **intensive even-aged** | 0,167 | 0,417 | 0,250 | 0,375 | 0,271 |
| **wood biomass** | 0,167 | 0,396 | 0,250 | 0,271 | 0,208 |

***Baden Wuerttemberg - Picea abies***

| | root rot | wind | bark beetle | snow | game |
|---|---|---|---|---|---|
| **close to nature** | 0,188 | 0,354 | 0,250 | 0,354 | 0,229 |
| **combined objectives** | 0,250 | 0,438 | 0,313 | 0,438 | 0,313 |
| **intensive even-aged** | 0,333 | 0,563 | 0,396 | 0,563 | 0,313 |
| **wood biomass** | 0,083 | 0,333 | 0,250 | 0,333 | 0,167 |

***Austria - Picea abies***

| | bark beetle | wind | snow | game | sawfly |
|---|---|---|---|---|---|
| **close to nature** | 0,375 | 0,354 | 0,438 | 0,292 | 0,125 |
| **combined objectives** | 0,333 | 0,354 | 0,479 | 0,250 | 0,188 |
| **intensive even-aged** | 0,458 | 0,458 | 0,583 | 0,333 | 0,188 |
| **wood biomass** | 0,250 | 0,333 | 0,500 | 0,146 | 0,250 |

***Silesia - Pinus sylvestris***

| | game | root rot | weevil | sawfly | wind |
|---|---|---|---|---|---|
| **close to nature** | 0,188 | 0,292 | 0,188 | 0,042 | 0,250 |
| **combined objectives** | 0,188 | 0,333 | 0,188 | 0,083 | 0,250 |
| **intensive even-aged** | 0,208 | 0,375 | 0,250 | 0,083 | 0,313 |
| **wood biomass** | 0,063 | 0,208 | 0,188 | 0,083 | 0,188 |

***Sweden - Pinus sylvestris***

| | root rot | weevil | game | bark beetle | wind |
|---|---|---|---|---|---|
| **close to nature** | 0,292 | 0,125 | 0,229 | 0,188 | 0,250 |
| **combined objectives** | 0,333 | 0,188 | 0,333 | 0,438 | 0,250 |
| **intensive even-aged** | 0,375 | 0,250 | 0,438 | 0,250 | 0,313 |
| **wood biomass** | 0,208 | 0,188 | 0,229 | 0,229 | 0,188 |

***Scotland - Pinus sylvestris***

| | game | wind | weevil | foliar disease | fire |
|---|---|---|---|---|---|
| **close to nature** | 0,271 | 0,417 | 0,375 | 0,479 | 0,479 |
| **combined objectives** | 0,333 | 0,521 | 0,521 | 0,646 | 0,583 |
| **intensive even-aged** | 0,333 | 0,521 | 0,521 | 0,646 | 0,583 |
| **wood biomass** | 0,271 | 0,375 | 0,500 | 0,604 | 0,396 |

***Scotland - Picea sitchensis***

| | game | wind | weevil | aphid | fire |
|---|---|---|---|---|---|
| **close to nature** | 0,271 | 0,417 | 0,375 | 0,438 | 0,479 |
| **combined objectives** | 0,271 | 0,396 | 0,438 | 0,333 | 0,438 |
| **intensive even-aged** | 0,333 | 0,521 | 0,521 | 0,396 | 0,583 |
| **wood biomass** | 0,271 | 0,375 | 0,500 | 0,292 | 0,396 |

**<u>Score of stand exposure to main hazards</u>** according to Forest Management Alternative in each case-study region – *uneven impact of damage*

***Aquitaine - Pinus pinaster***

| | defoliator | stem borer | wind | fire | root rot |
|---|---|---|---|---|---|
| **close to nature** | 0,833 | 6,438 | 18,813 | 18,813 | 19,167 |
| **combined objectives** | 1,250 | 6,375 | 18,792 | 18,792 | 19,375 |
| **intensive even-aged** | 1,250 | 8,521 | 25,063 | 25,063 | 25,625 |
| **wood biomass** | 1,667 | 6,250 | 18,750 | 18,750 | 19,583 |

***Portugal - Eucalyptus sp.***

| | leaf rust | leaf beetle | gall insect | fire | stem canker |
|---|---|---|---|---|---|
| **close to nature** | 1,250 | 8,750 | 1,875 | 19,417 | 13,146 |
| **combined objectives** | 1,250 | 8,750 | 1,875 | 19,417 | 13,146 |
| **intensive even-aged** | 1,667 | 11,667 | 2,500 | 25,875 | 17,521 |
| **wood biomass** | 1,667 | 9,583 | 2,500 | 19,583 | 13,333 |

***Baden Wuerttemberg - Picea abies***

| | root rot | wind | bark beetle | snow | game |
|---|---|---|---|---|---|
| **close to nature** | 6,375 | 19,292 | 13,000 | 19,292 | 6,792 |
| **combined objectives** | 6,438 | 19,563 | 13,250 | 19,563 | 7,063 |
| **intensive even-aged** | 8,583 | 25,875 | 17,458 | 25,875 | 7,063 |
| **wood biomass** | 8,333 | 25,833 | 17,500 | 25,833 | 9,167 |

***Austria - Picea abies***

| | bark beetle | wind | snow | game | sawfly |
|---|---|---|---|---|---|
| **close to nature** | 25,125 | 25,479 | 26,313 | 6,854 | 1,250 |
| **combined objectives** | 25,083 | 25,667 | 26,917 | 7,000 | 1,875 |
| **intensive even-aged** | 33,458 | 34,021 | 35,271 | 9,146 | 1,875 |
| **wood biomass** | 25,000 | 25,833 | 27,500 | 7,083 | 2,500 |

***Silesia - Pinus sylvestris***

| | game | root rot | weevil | sawfly | wind |
|---|---|---|---|---|---|
| **close to nature** | 6,375 | 13,042 | 18,750 | 0,417 | 18,813 |
| **combined objectives** | 6,375 | 13,458 | 18,750 | 0,833 | 18,813 |
| **intensive even-aged** | 8,458 | 17,625 | 25,000 | 0,833 | 25,063 |
| **wood biomass** | 6,250 | 13,333 | 18,750 | 0,833 | 18,750 |

***Sweden - Pinus sylvestris***

| | root rot | weevil | game | bark beetle | wind |
|---|---|---|---|---|---|
| **close to nature** | 12,500 | 18,750 | 13,042 | 6,792 | 18,813 |
| **combined objectives** | 18,750 | 21,250 | 13,458 | 13,458 | 18,813 |
| **intensive even-aged** | 25,000 | 0,250 | 17,625 | 10,188 | 25,063 |
| **wood biomass** | 18,750 | 7,917 | 13,333 | 7,917 | 18,750 |

***Scotland - Pinus sylvestris***

| | game | wind | weevil | foliar disease | fire |
|---|---|---|---|---|---|
| **close to nature** | 7,208 | 25,542 | 26,250 | 26,729 | 25,604 |
| **combined objectives** | 9,708 | 34,083 | 35,208 | 35,896 | 34,146 |
| **intensive even-aged** | 9,708 | 34,083 | 35,208 | 35,896 | 34,146 |
| **wood biomass** | 7,958 | 25,875 | 27,500 | 28,354 | 25,896 |

***Scotland - Picea sitchensis***

| | game | wind | weevil | aphid | fire |
|---|---|---|---|---|---|
| **close to nature** | 20,125 | 26,250 | 7,208 | 25,542 | 25,604 |
| **combined objectives** | 8,208 | 26,875 | 7,583 | 25,708 | 25,750 |
| **intensive even-aged** | 10,333 | 35,208 | 9,708 | 34,083 | 34,146 |
| **wood biomass** | 2,542 | 27,500 | 7,958 | 25,875 | 25,896 |