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Research, part of a Special Feature on Sustainability Impact Assessment of Forest Management Alternatives in Europe

A Multicriteria Risk Analysis to Evaluate Impacts of Forest Management Alternatives on Forest Health in Europe

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ABSTRACT. Due to climate change, forests are likely to face new hazards, which may require adaptation of our existing silvicultural practices. However, it is difficult to imagine a forest management approach that can simultaneously minimize all risks of damage. Multicriteria decision analysis (MCDA) has been developed to help decision makers choose between actions that require reaching a compromise among criteria of different weights. We adapted this method and produced a multicriteria risk analysis (MCRA) to compare the risk of damage associated with various forest management systems with a range of management intensity. The objective was to evaluate the effect of four forest management alternatives (FMAs) (i.e., close to nature, extensive management with combined objectives, intensive even-aged plantations, and short-rotation forestry for biomass production) on biotic and abiotic risks of damage in eight regional case studies combining three forest biomes (Boreal, Continental, Atlantic) and five tree species (*Eucalyptus globulus*, *Pinus pinaster*, *Pinus sylvestris*, *Picea sitchensis*, and *Picea abies*) relevant to wood production in Europe. Specific forest susceptibility to a series of abiotic (wind, fire, and snow) and biotic (insect pests, pathogenic fungi, and mammal herbivores) hazards were defined by expert panels and subsequently weighted by corresponding likelihood. The PROMETHEE ranking method was applied to rank the FMAs from the most to the least at risk. Overall, risk was lower in short-rotation forests designed to produce wood biomass, 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 had low overall risk, due to lower stand value exposed 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 the four FMAs were detected between the combinations of forest biomes and tree species.

Key Words: *abiotic; biotic; damage; hazard; MCRA; silviculture*

INTRODUCTION

In the context of global climate change, European forests are likely to face an increasing number of threats. Current climate change scenarios are predicting an increase in mean temperatures and in the frequency or severity of droughts, and possibly also of wind storms in Europe (Solomon et al. 2007, Blenkinsop and Fowler 2007, Della-Marta et al. 2009). In many regions, forests are increasingly prone to fire damage as a result of prolonged drought periods (Kirilenko and Sedjo 2007). Many forest pests and pathogens have the potential to cause increasing damage as a result of these changes, either directly through higher intrinsic population growth and geographical spread (Vanhanen et al. 2007, Berggren et al. 2009), or indirectly via higher tree susceptibility (Battisti et al. 2005, Desprez-Loustau et al. 2006, Rouault et al. 2006). As a consequence of increasing globalization, with more frequent trade and passenger traffic between continents, there is also an increasing number of alien pest and pathogen species that have become established in Europe and may cause severe damage to forest ecosystems (Roques et al. 2009) in the future. The major challenges for forest science are, therefore, to analyze present and future risks and their potential impact as well as to translate their outcomes into forest management recommendations.

In its scientific/technical meaning, the term risk can be described as the probability of loss or damage due to the occurrence of a hazard (Kaplan and Garrick 1980, Hanewinkel et al. 2011). More precisely, the natural disaster literature (for example, Kron 2002, 2005, Chen et al. 2004, de Moel et al. 2011) has identified three main components that determine the risk: (1) the hazard that is a latent damaging event for some elements, (2) the susceptibility that corresponds to the lack of resistance of the elements to damaging forces of the hazard, and (3) the values of the elements exposed to the hazard and susceptible to being lost. A risk analysis is, then, a probabilistic approach (Hanewinkel et al. 2011) that quantifies the negative consequences of a hazard by multiplying its likelihood by the levels of susceptibility and value. We used this theoretical framework to estimate the risk of forest damage by combining natural hazard likelihoods, forest stand susceptibility to these damaging agents, and forest product values that can be lost if nothing is done to prevent the damage.

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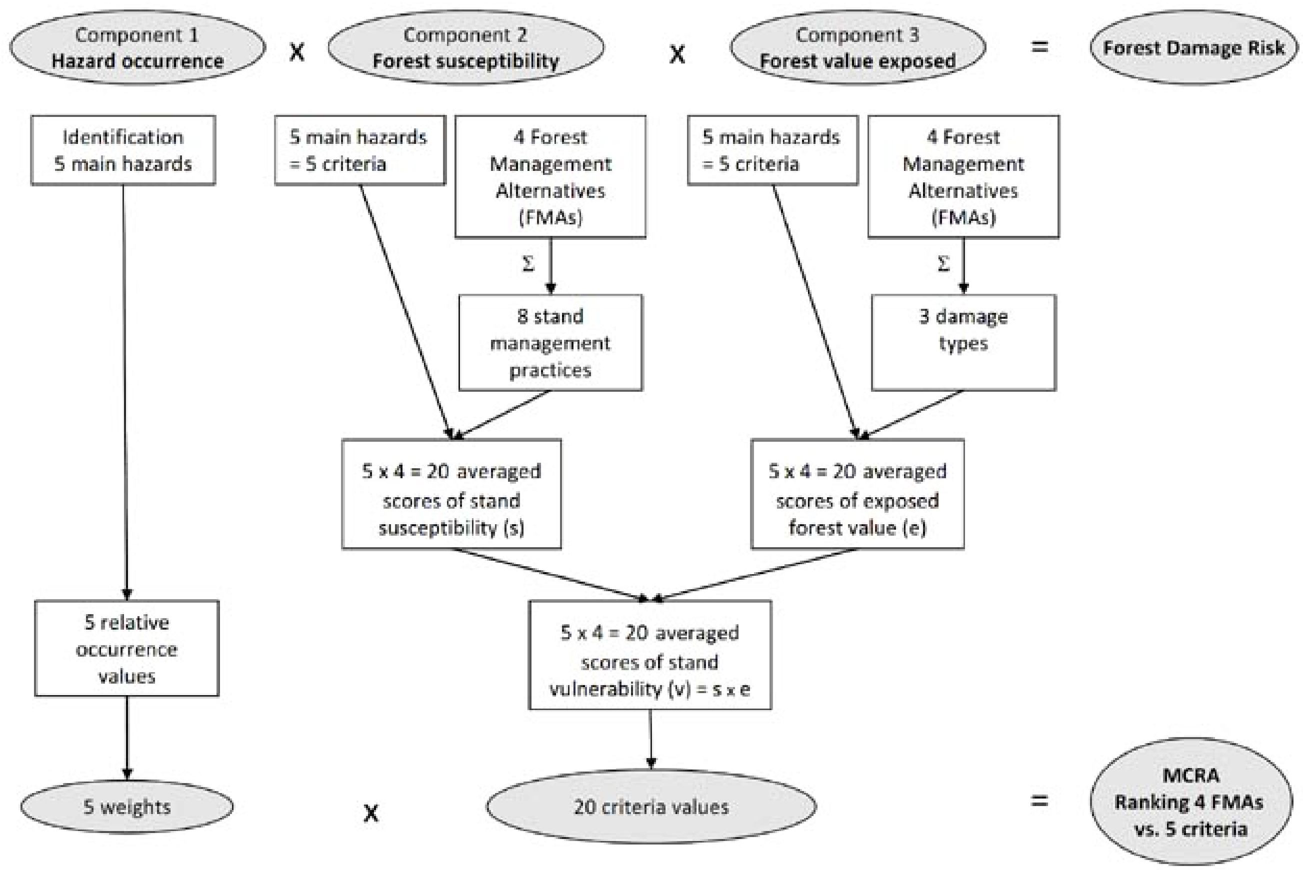
Recently, a comprehensive review of the scientific literature has shown that forest stand management may have an effect on all three components of the risk of damage (Jactel et al. 2009). This knowledge could be used to develop formal statistical, predictive risk models for managed forests. Several studies have compared the theoretical effect of different forest management regimes on stand susceptibility to specific damaging agents such as strong winds in conifer stands (e.g., Gardiner and Quine 2000, Holecy and Hanewinkel 2006, Schelhaas 2008), ice in loblolly pine (*Pinus taeda* (L.)) stands (Goodnow et al. 2008), bark beetles in Norway spruce (*Picea abies* (L.) Karst.) forests (Seidl et al. 2009), root rot fungi (Pukkala et al. 2005), and game (roe deer) in Norway spruce and European larch (*Larix decidua* Mill.) forests (Vospernik and Reimoser 2008) using sophisticated damage functions and simulations from tree growth models. However, these models cannot be used to integrate several disturbance effects at the same time and to run simulations in different, contrasting regions. This is important, as a specific forestry practice may enhance stand resistance to one damaging agent while increasing stand susceptibility to other causes of damage (Jactel et al. 2009). In addition, damage from one hazard may increase the susceptibility of the forest to a secondary hazard (Lindelöw and Schröder 2008). As the number of hazards taken into consideration increases, it becomes more difficult to identify a forest management alternative that simultaneously minimizes all risks of damage. The same type of problem arises when forest managers have to deal with conflicts about resource use for timber harvesting, recreation, or biodiversity conservation (Ananda and Herath 2003). Evaluation of sustainable forest management involves environmental, social, and economic criteria, and it is often difficult to find a compromise between their potentially conflicting requirements and to identify management alternatives that can maximize the benefits of all of them (Ananda and Herath 2009). In response to these difficulties, multicriteria decision analysis (MCDA) tools are increasingly being used (Ananda and Herath 2009, Behzadian et al. 2010).

In this paper, we have adapted MCDA tools to compare forest management alternatives in relation to multiple risk factors. We suggest naming the method a “Multicriteria Risk Analysis” (MCRA). This is an innovative approach to forest risk assessment, which considers several risks at the same time and uses several evaluation criteria. MCDA was developed to help rank several alternatives from the worst to the best based on multiple, often conflicting, criteria (Behzadian et al. 2010). One of the main advantages of MCDA is that it allows consideration of a large number of criteria that may be measured on completely different scales, unlike other assessment methods such as classical risk analyses (Huth et al. 2005). MCDA models have been used in forest planning in regard to several objectives such as biodiversity (Huth et al. 2005, Lexer and Seidl 2009), carbon sequestration (Briceno-Elizondo et al. 2008), watershed management (Sonneveld and Albersen 1999), wildlife management and conservation (Bock and Salski 1998, Kangas and Kuusipalo 1993), and landscape attributes (Kangas et al. 2001, Palma et al. 2007).

Several MCDA algorithms are available (see a review in Bhezadian et al. 2010). In this paper, we use PROMETHEE II, a MCDA method that was developed to provide a ranking of the compared alternatives as a function of their performance against several criteria (Brans et al. 1984, Brans and Vincke 1985). This method is considered to provide relevant and reliable results (Brans et al. 1986, Kiker et al. 2005, Zhang et al. 2009). It is also user friendly and allows sensitivity analyses through the ability to change preference functions or criteria weights (Hermans et al. 2007). Although the PROMETHEE method is widely used in academic research—Behzadian et al. (2010) found 217 papers published since its development in 1985—to our knowledge, it has never been applied to risk management in forests. Krist et al. (2010) used a multicriteria framework to produce multiple insect and disease risk maps in U.S. forests but they did not use a MCDA algorithm to allow decision making about pest management. Recently, the preference functions of the PROMETHEE methodology were employed by Seidl et al. (2011) to aggregate multiple sustainable forest management criteria, including vulnerability to bark beetles, snow, and storm damage, but then they used an ecosystem model to compare management strategies. In this study, we sought to adapt the method in order to rank the performance of different forest management alternatives with regard to overall reduction of forest vulnerability to several disturbance agents, where each agent is considered a criterion. We argue that to provide forest managers with helpful recommendations to reduce or alleviate the risk of damage, we may have to shift from an optimization-based approach, which provides quantitative outcomes from statistically based modeling but needs accurate inputs and has a narrow application domain, to MCRA. More comprehensive, although less quantitative, the MCRA approach uses semi-quantitative inputs, which can be readily implemented across a wide range of hazards and geographic locations.

The goal of the present contribution is not to analyze and prescribe the best forest management solution for a specific problem in a specific region. Instead, our goal is to look for the potential and robustness of our method by including a large range of hazard factors and various regions of Europe in a multicriteria approach. The objective of this paper is, therefore, to present an adaptation of the MCDA method for risk assessment and to draw an example of this innovative approach for comparing the impact of four forest management alternatives on European forest damage risk. This problem is comparable to a decision-making problem for forest managers who have to find the forest management alternative that would best minimize the risk of damage from several hazards.

Fig. 1. Conceptual flow diagram of MCRA methodology for a given regional case study.



METHODS

Principles

We developed a stepwise procedure of MCRA by analogy with the MCDA approach. To rank the four forest management alternatives (FMAs), we used as criteria stand vulnerability to the five most frequent biotic or abiotic hazards in each of the eight regional case studies. Vulnerability was defined as the product of stand susceptibility (predisposition to damage) to a particular hazard by its exposed value. Exposed value is defined by the value that is at stake, i.e., to what extent forest products will be impacted by the hazard. Here, we only considered wood biomass and timber as forest products (other ecosystem services such as provision of food or biodiversity were not taken into account). Therefore, those forests with a high value at stake will automatically have a tendency to higher risk. We used as the weight of each criterion the likelihood of hazards occurring (Fig.1; Table 1). Because risk was defined as the product of stand vulnerability to a particular hazard by the likelihood of this hazard (Kron 2002, Jactel et al. 2009), the complete ranking for the FMAs was based on pairwise comparison of risk associated with different alternatives.

Table 1. Correspondences between objectives and vocabulary of Multicriteria Decision Analysis (MCDA) and Multicriteria Risk Analysis (MCRA)

MCDA	MCRA
Solve a decision problem	Solve a forest management problem
Rank alternatives in order of increasing preference according to several criteria	Rank FMAs[†] in order of decreasing risk of damage by several hazards
Alternative	Forest management alternative
Criteria	Vulnerability to several hazards
Weight	Likelihood of the hazard

[†] FMA, forest management alternative

To evaluate the robustness of MCRA, we compared the outcomes of the procedure in eight different regional case studies for which we could collect sufficient information about susceptibility to biotic and abiotic hazards. They comprised three forest biomes and five tree species relevant to wood production in Europe (Table 2). The five most frequent biotic

Table 2. List of regional case studies used in the MCRA

Country	Region	Forest Biome	Tree species	Common name	Acronym	Expert panel[†]
Portugal	Central	Atlantic	*Eucalyptus globulus*	Eucalypt	PT-Euc	ISA, RAIZ, INRB
France	Aquitaine	Atlantic	*Pinus pinaster*	Maritime pine	FR-Mar	INRA, DSF, CRPF
United Kingdom	Scotland	Atlantic	*Picea sitchensis*	Sitka spruce	UK-Sit	FR, ALTERRA
United Kingdom	Scotland	Atlantic	*Pinus sylvestris*	Scots pine	UK-Sco	FR, ALTERRA
Poland	Silesia	Boreal	*Pinus sylvestris*	Scots pine	PL-Sco	IBL
Sweden	Central	Boreal	*Pinus sylvestris*	Scots pine	SU-Sco	SLU, IBL
Germany	Baden-Württemberg	Continental	*Picea abies*	Norway spruce	GE-Nor	ALUFR
Austria	Central	Continental	*Picea abies*	Norway spruce	AU-Nor	BOKU

[†] Institutions to which experts belonged: ISA, Instituto Superior de Agronomia, Lisbon, Portugal; RAIZ, Instituto de Investigação da Floresta e Papel, Lisbon, Portugal; INRB, Instituto Nacional de Recursos Biológicos, Lisbon, Portugal; INRA, Institut National de la Recherche Agronomique, Bordeaux, France; DSF, Département de la Santé des Forêts, Bordeaux, France; CRPF, Centre Régional de la Propriété Forestière, Bordeaux, France; FR, Forest Research, Scotland, United Kingdom; ALTERRA, Centre for Ecosystem Studies, Wageningen, The Netherlands; IBL, Forest Research Institute, Kraków, Poland; SLU, Swedish University of Agricultural Sciences, Uppsala, Sweden; ALUFR, Albert-Ludwigs-University, Freiburg, Germany; BOKU, University of Natural Resources and Life Sciences, Vienna, Austria;

and abiotic hazards in each case study were listed according to expert knowledge. They were categorized into the main biotic and abiotic groups to allow comparison between regions.

In each region, we gathered a panel (a total of seven panels for the study) of at least one expert per criterion (hazard type). Experts were highly qualified researchers in forest ecology with expertise on the hazard types retained in our analysis (fire, storm, insects, game, and pathogens) belonging to the leading universities or research institutes within each region (Table 2).

In PROMETHEE analyses, criteria are weighted according to their importance on a relative percentage basis with the sum of weights being equal to 1. The relative likelihood of hazards (weights of vulnerability criteria) was then quantified by experts according to their knowledge, or from inventory data whenever available. They estimated the percentage of trees affected by each of the five hazards at the stand level, according to the patterns of occurrence observed during the last 30–50 yrs. Then, percentages were transformed in relative proportions (sum = 100%) as required by the PROMETHEE method (Table 3). A relative likelihood (weight) of 50% for hazard 1 and 5% for hazard 2 means that hazard 1 is ten times more likely to occur than hazard 2.

To allow comparison between regional case studies, we considered the same four FMAs, as part of a gradient of increasing silvicultural intensity: close-to-nature forestry, combined objectives, intensive even-aged, and wood biomass production forestry. Their main objectives and basic principles are summarized in Table 4 (for more details, see Duncker et al. 2012).

Multicriteria Decision Matrix

The starting point of a multicriteria analysis is the decision matrix, which describes the performance of the alternatives to be ranked (as rows) with respect to selected criteria (as columns) (Belton and Stewart 2002, Palma et al. 2007). To build this matrix, we evaluated the susceptibility of the different FMAs with respect to the five main hazards in each regional case study. This was carried out by characterizing eight successive silvicultural operations for each FMA: site selection, soil preparation, stand composition, tree genotype selection, regeneration process, understory management, tree thinning and pruning, and final harvesting. For each silvicultural operation, the management options (e.g., pure vs. mixed for the stand composition) usually undertaken or expected to be undertaken by forest managers in each regional case study were assessed for their potential effect on stand susceptibility. This was done by experts within the scope of the European Integrated Project EFORWOOD and using the review paper of Jactel et al. (2009) as a common framework.

Regional experts scored the effect of each management option on stand susceptibility (*S*) to each hazard ($S_{a,i,j}$). They identified the options that had no effect on tree susceptibility to a specific hazard (i.e., reference standard options) and a score of 1 was given to these options ($S_{a,i,j}$ = 1). Then, the experts gave a score of 0.50 or 0.75, respectively, to any other option that would greatly or moderately decrease stand susceptibility and a score of 1.25 or 1.50, respectively, if it would moderately or greatly increase stand susceptibility compared with the reference standards. Then, for each FMA, scores were averaged across silvicultural operations for each hazard according to

$$S_{a,i} = \frac{\sum_{j=1}^{8} S_{a,i,j}}{8} \qquad (1)$$

where $a \subset [1, 4]$ is the FMA, $i \subset [1, 5]$ is the hazard (criterion); $j \subset [1, 8]$ is the silvicultural operation; $S_{a,i,j}$ is the score of stand susceptibility to the hazard *i* as a result of the application of a

Table 3. Name and relative likelihood (weight) of the five most frequent hazards in the eight regional case studies

The relative likelihood of hazards was estimated as the percentage of trees affected by each of the five hazards at the stand level, according to the patterns of occurrence observed during the last 30–50 years. Then percentages were transformed in relative proportions (sum = 100%)

Case study	Hazard #1	Hazard #2	Hazard #3	Hazard #4	Hazard #5
PT-Euc	leaf rust *M. spp.* 43%	leaf beetle *G. scutellatus* 26%	gall insect *C. spatulata* 26%	fire 4%	stem canker *B. dothidea* 1%
FR-Mar	defoliator *T. pityocampa* 47%	stem borer *D. sylvestrella* 47%	wind 3%	fire 2%	root rot *H. annosum* 1%
UK-Sit	game *C. elaphus* 81%	wind 9%	weevil *H. abietis* 5%	aphid *E. abietinum* 4%	fire 1%
UK-Sco	game *C. elaphus* 81%	wind 9%	weevil *H. abietis* 5%	foliar disease *D. septosporum* 4%	fire 1%
PL-Sco	game *C. elaphus* 47%	root rot *H. annosum* 19%	weevil *H. abietis* 15%	sawfly *A. nemoralis* 12%	wind 7%
SU-Sco	root rot *H. annosum* 38%	weevil *H. abietis* 28%	game 19%	bark beetle *I. typographus* 8%	wind 8%
GE-Nor	root rot *H. annosum* 58%	wind 20%	bark beetle *I. typographus* 20%	snow 1%	game *C.s elaphus* 1%
AU-Nor	bark beetle *I. typographus* 25%	wind 25%	snow 20%	game *C. elaphus* 20%	sawfly *P. abietina* 10%

Most frequent biotic hazards : *Mycosphaerella* spp, *Gonipterus scutellatus, Ctenarytaina spatulata, Botryosphaeria dothidea, Thaumetopoea pityocampa, Dioryctria sylvestrella, Cervus elaphus, Heterobasidion annosum, Hylobius abietis, Elatobium abietinum, Dothistroma septosporum, Acantholyda nemoralis, Ips typographus, Pristiphora abietina.*

particular option during the silvicultural operation *j*, where $S_{a,i,j} \subset [0.50; 0.75; 1.00; 1.25; 1.50]$. The scoring was made independently for each region to avoid any bias. The complete list of scores is provided in Appendix 1.

To evaluate stand value exposed to each hazard, we used a three-step approach. First, we considered three types of damage: tree mortality, loss in biomass production, and loss in wood quality. We scored their relative importance (*I*) for each FMA, using a five-level scale: 0, 0.25, 0.50, 0.75, and 1 for null, low, moderate, high, and very high, respectively. This scoring of relative importance was independent of the type of hazard. The scoring was made independently for each region to avoid any bias. The complete list of scores is given in Appendix 2. Second, we estimated the contribution of hazards (*C*) to the three damage types, using a five-level scale: 0, 0.25, 0.50, 0.75, and 1 for null, low, moderate, high, and very high, respectively. The contribution of a particular hazard to a particular type of damage was considered as constant, regardless of the stand management. The complete list of scores is given in Appendix 3. Third, we scored the exposed value of each FMA to each hazard by multiplying scores of damage importance according to the three damage types by the score of hazard impacts in order to capture to what extent each hazard may affect the values associated with wood production in the different FMAs. Then, we averaged scores across damage types for each hazard to estimate a mean exposed value (*E*) to each hazard according to

$$E_{a,i} = \frac{\sum_{k=1}^{3} C_{i,k} \times I_{a,k}}{3} \qquad (2)$$

For a given FMA $a \subset [1, 4]$, the hazard (criterion) is *i*, $i \subset [1, 5]$, the type of damage is *k*, $k \subset [1, 3]$, $C_{i,k}$ is the contribution of hazard *i* to damage type *k*, $C_{i,k} \subset [0.25; 0.50; 0.75; 1.00]$, $I_{a,k}$ is the importance of the damage *k* for stand value, $I_{a,k} \subset [0.25; 0.50; 0.75; 1.00]$, $E_{a,i}$ is the score of value exposed to the hazard *i* as a result of its effect on tree mortality, loss in biomass production, and loss in wood quality.

Ultimately, we combined susceptibility and exposed value (by multiplying the scores) to define stand vulnerability (*V*) to each hazard, according to

Table 4. Main objectives and basic principles of the four forest management alternatives compared in the MCRA

FMAs	Objectives	Principles
Close to nature	Mimic or emulate natural processes	Natural regeneration, mixed stands, no site preparation or thinnings, long rotation length, selection harvesting
Combined objectives	Combine production and ecological objectives at the stand level	Natural regeneration, mixed stands, site cultivation, and thinnings, rotation length adapted to optimal wood productivity, harvesting limited to solid wood
Intensive even-aged	Optimize wood production	Plantation, monocultures, even-aged structure, site preparation, cultivation, fertilization, regular thinnings, rotation length adapted to the economic return, clearcut harvesting
Wood biomass	Produce the greatest amount of wood biomass	Plantation, monocultures, even-aged structure, fast-growing species, site preparation, cultivation, fertilization, short rotation, clearcut harvesting, removal of residues

$$V_{a,i} = S_{a,i} \times E_{a,i} \qquad (3)$$

We could then draw eight multicriteria decision matrices (one for each regional case study), with the 20 vulnerability scores $V_{a,i}$ obtained for each combination of the four FMAs (*a*) by the five hazard types (*i*). The eight matrices are given in Appendix 4.

Preference Functions

We used Decision Lab® 2000 software (2003) to process data. We performed PROMETHEE II analyses (Brans et al. 1984, 1986) to make a complete ranking of the four FMAs according to their performance (impact on stand vulnerability).

For each criterion (hazard), a preference matrix is constructed to indicate for each pair of alternatives which one is preferred, based on whether the criterion should be maximized or minimized. Then, for each criterion, a preference function is chosen to transform differences between the values obtained by the two alternatives, expressed with the specific scale of the criterion, into a standardized preference degree ranging from 0 to 1. The values of an indifference threshold (*q*) and of a strict preference threshold (*p*) are fixed by the decision maker. In this case, decision makers were the experts. Criteria are further weighted according to the importance attached to each criterion (with the sum of weights being equal to 1). A weighted preference index is then calculated for each pair-wise comparison to provide an integrated preference across all criteria of one alternative over the other. Ultimately, an outgoing flow ($\phi^+_{(a)}$) is calculated for each alternative to estimate how far it outranks other alternatives, an incoming flow ($\phi^-_{(a)}$) is calculated to estimate how far it is outranked by other alternatives, and a net flow is calculated as the difference between the two unidirectional flows ($\phi_{(a)} = \phi^+_{(a)} - \phi^-_{(a)}$) (see Ghafghazi et al. [2010] and Bhezadian et al. [2010] for details about stepwise procedure for PROMETHEE II).

Because preference was likely to decrease proportionally to vulnerability, we used the V-shaped model as preference function. As *p* value (preference threshold), we used the maximum, observed value of stand vulnerability in each regional case study (i.e., eight different *p* values). Because the main objective of the study was to find the FMA that most reduces the risk of damage, we set the decision rule to "minimize" all criteria, i.e., minimize scores of vulnerability to any hazard. We made a paired Friedman's test to compare the rankings ($\phi_{(a)}$ values) among the eight regional case studies. We used the multiple scenarios tool in Decision Lab® to combine the eight multicriteria decision matrices and then provide an overall complete ranking of the four FMAs, irrespective of the regional case studies.

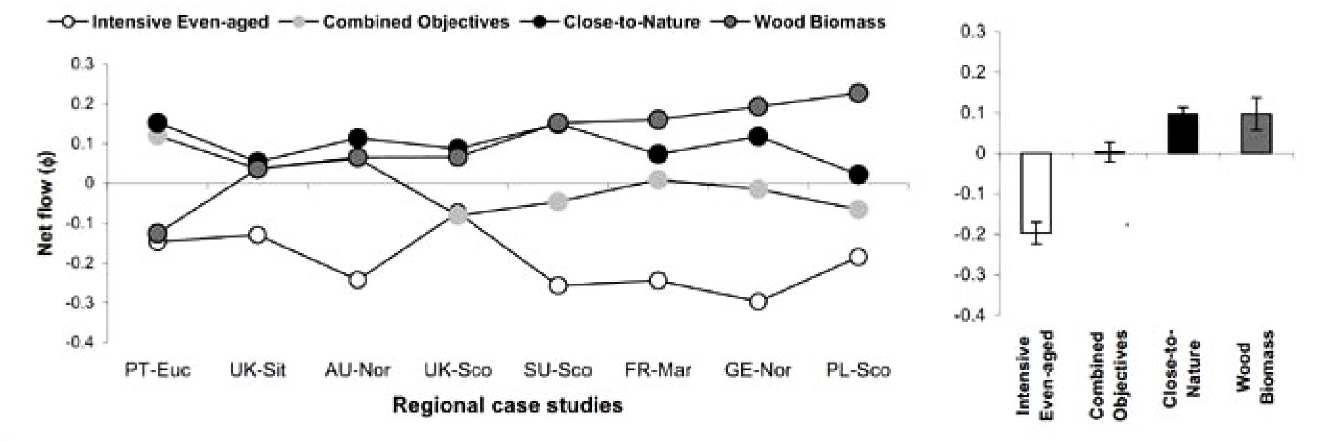
Sensitivity Tests

We performed three sensitivity tests. First, we reset all relative weights to equal weights to rank the FMAs irrespective of the hazard occurrence, i.e., according only to their vulnerability (Appendix 4). Second, we tested another range of scores for the relative importance of the three types of damage, differing by three orders of magnitude, in calculation of exposed values (Appendix 2). 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 to as "uneven importance," whereas the option with the same range of scores for all types of damage will be referred as "even importance." Third, we reset all scores of exposed value (Table 3) equal to 1 in order to rank the FMAs according to their impact on biological damage, regardless of their consequence for forest stand values.

Carrying Out the Study

Three workshops were organized with all the co-authors of the study to refine the MCRA procedure. The principle of MCDA was discussed for its applicability to risk analysis in a first workshop. A prototype of MCRA was made using the French case study and discussed at a second workshop in order to refine the method of scoring. Then, seven expert panels were set up (one per country), involving at least one co-author of the study plus local experts, where possible, so all criteria were covered. A first round of scoring was made for each case study during face-to-face workshops or conference calls. Experts aggregated statistics from the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests in Europe (ICP-Forest), national agencies in charge of forest condition monitoring (e.g., National Forest Inventories or Forest Health Departments) and

Fig. 2. Ranking of forest management alternatives (FMAs) according to impact on risk of biotic and abiotic damage across eight different regional case studies (left-hand side) and for overall results (right-hand side). FMAs with higher net flow (Φ) are preferred to those with lower net flow.



their own observation at the regional level to estimate the scores of hazard occurrence. They used the scientific literature to qualify the effect of stand management operations on stand susceptibility to main hazards (in particular the Jactel et al. (2009) paper to which most of them contributed) and the contribution of hazards to damage. They interviewed local forest advisers from state and private forest organizations to refine their estimates of the relative importance of the three types of damage for each FMA. Matrices of scores were then circulated by email among countries to detect possible outliers. MCRA were run with these scores and outcomes were discussed at a third workshop to check for possible causes of discrepancy. A second round of scoring was organized at the level of the expert panels to correct for incoherencies, but scores were not homogenized at the European scale in order to maintain the among-regions variability. A final MCRA was made for each region. For the sake of consistency, all computations using the Decision Lab® software were done by the same person (the lead author).

RESULTS

Ranking of Forest Management Alternatives According to Their Damage Risk

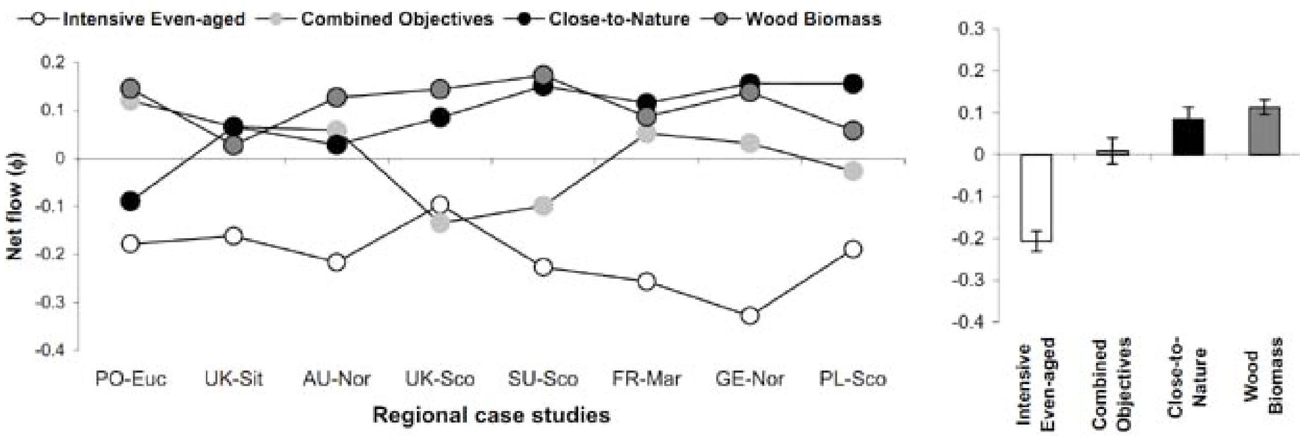
The ranking of the four FMAs according to their impact on biotic and abiotic risk of damage (five main hazards) displayed similar patterns over most of the eight regional case studies (Fig. 2a). The intensive even-aged alternative was almost always ranked as the most at risk, whereas the close-to-nature and the wood biomass alternatives were consistently considered as the least at risk. The only deviation from this trend concerned the case study of eucalyptus (*Eucalyptus* sp.) forests in Portugal, for which the close-to-nature alternative was considered equally at risk as the intensive even-aged. However, there were no significant differences in the relative (within each region) risk ranking ($\phi_{(a)}$ values) of the four FMAs between different regions according to a Friedman test (Q_{obs} = 1.41, Q_{crit} = 14.07, P = 0.98). This suggests that similar FMAs are perceived to have similar impacts on the risk to forests irrespective of tree species and climate conditions, although the low statistical power of our test (n = eight case studies) precludes excessive generalization. We were then able to combine the performance matrices of the eight regions to provide an overview of FMA rankings (Fig. 2b).

Sensitivity Tests

When all criteria weights were reset to equal, i.e., when the difference in hazard occurrence was ignored, the mean ranking of FMAs did not change (Fig. 3). Overall, the close-to-nature and the wood biomass alternatives showed the least vulnerability, whereas the intensive even-aged alternative remained the most vulnerable, and the combined objectives alternative was intermediate. Again, there were no significant differences in FMA ranking among the eight regional case studies (Q_{obs} = 1.33, Q_{crit} = 14.07, P = 0.99).

When greater importance was given to tree mortality than to tree growth loss and wood quality loss (“uneven importance”), a change in FMA ranking was observed (Fig.4). The wood biomass alternative was no longer considered to be the one least at risk, but ranked third in terms of preference. However, the intensive even-aged alternative remained the most at risk and the close-to-nature alternative was the least at risk. In this test, the Portuguese eucalyptus forests case study behaved similarly to other regions, with wood biomass now poorly ranked and close-to-nature highly ranked. There were no

Fig. 3. Ranking of FMAs according to vulnerability to biotic and abiotic hazards, i.e., irrespective of hazard occurrence (equal weights in MCRA) across eight different regional case studies (left-hand side) and for overall results (right-hand side).



significant differences in FMA ranking among the eight regional case studies (Q_{obs} = 1.75, Q_{crit} = 14.07, P = 0.97).

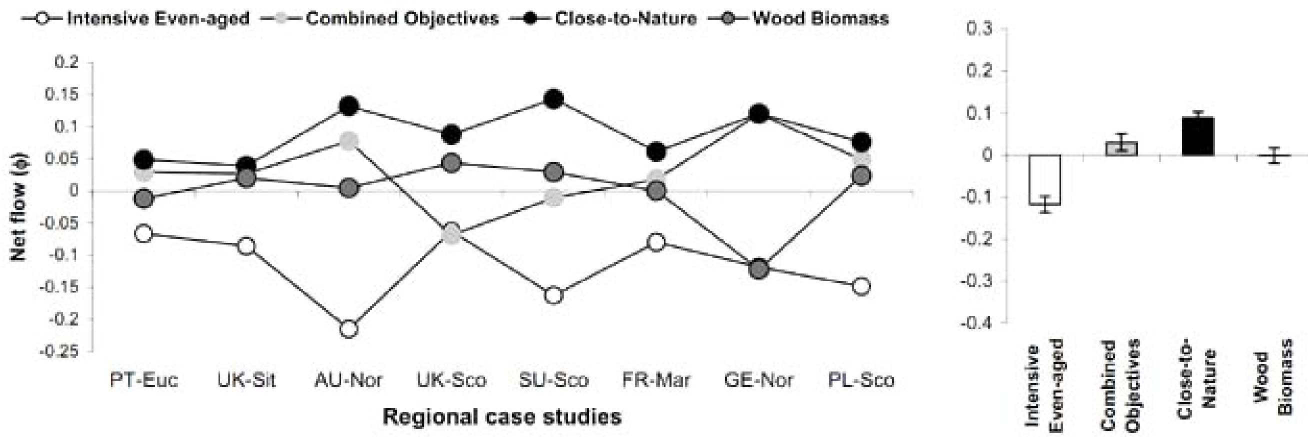
When all scores of exposed value were set equal to 1 (i.e., comparison of FMA impacts on biological damage regardless of forest stand values), the close-to-nature alternative was the FMA least susceptible to hazards, whereas intensive even-aged and wood biomass both had high stand susceptibility (Fig. 5). The eucalyptus case study was also comparable to the other case studies. There were no significant differences in FMA ranking among the eight regional case studies (Q_{obs} = 0.33, Q_{crit} = 14.07, P = 0.99).

DISCUSSION

Forests are expected to fulfill many functions, such as recreation, wood production, nature conservation, and protection of natural resources and human infrastructure. Optimal forest management should take all these functions into account, resulting in integration or segregation of functions and leading to different ways of managing different parts of the forest. Maintaining the health of the forest should be an integral part of such forest management strategies. The economic, social, and environmental implications of forest protection are a major concern (e.g., Kallio et al. 2006). However, due to the multiple hazards affecting forest trees in different ways and the contrasting effects of different management strategies on different hazards, it is not straightforward to analyze all possible forest management options and decide on the best solutions for maximizing forest protection objectives. In this study, we propose a new method, based on MCDA tools, to help optimize forest management options in relation to multiple hazards and criteria (i.e., a Multicriteria Risk Analysis). Multicriteria decision analysis and the PROMETHEE method of ranking have been successfully used in forest research to identify optimum tree-harvesting scenarios that would maximize yield while reducing the impact on canopy structure and composition in rain forests (Huth et al. 2005) and to optimize the establishment of agroforestry at the landscape level (Palma et al. 2007). We followed the same methodology and tried to design a specific tool, Multicriteria Risk Analysis, which allows comparison of the effect of different FMAs on the impact of several biotic and abiotic hazards. Using simple assumptions, expert knowledge, and semi-quantitative estimates of hazard occurrence, stand susceptibility, and implicated forest product values, we were able to complete a risk analysis for eight case study areas across Europe.

The panel groups consisted of groups of experts in natural science, highly experienced with the hazard types considered (fire, storm, insects, game, and pathogens). This can be considered a guarantee of accuracy of the scores of occurrence and susceptibility. However, they used their own perception of exposed values. At the same time, it needs to be remembered that risk assessment not only depends on the technical information available to the individual (Kaplan and Garrick 1980) but is also a subjective matter, as different individuals may have different attitudes toward risk, usually expressed as risk aversion (Hanewinkel et al. 2011). It is increasingly accepted that individual or collective risk aversion needs to be better taken into account (Cardona 2003) because there are some discrepancies between objective assessment of expected loss and human perception of possible loss (Nicholson 1995, Plattner 2006). In our risk analysis, two types of scores were likely to have been particularly sensitive to subjective estimates: hazard occurrence (e.g., storm damage was not considered particularly important by experts due to the long return periods between storms, whereas forest managers

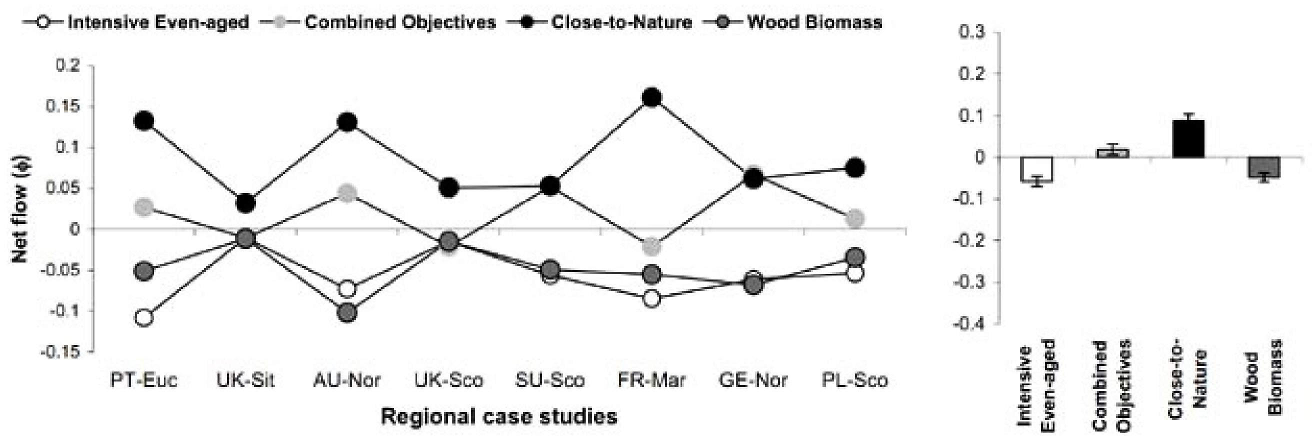
Fig. 4. Ranking of FMAs according to impact on risk of damage, giving more importance (“uneven importance” test) to tree mortality than tree growth loss and wood quality loss, across eight different regional case studies (left-hand side) and for overall results (right-hand side).



consider storms more important because of their long-lasting effects) and the values at stake. We addressed this problem by performing sensitivity analyses, where hazard occurrences were set equal and scores of exposed value were changed (with higher values for more dramatic impacts, such as tree mortality). We did not observe any significant changes in FMA ranking when hazard likelihood was changed, but when greater importance was given to tree mortality the wood biomass FMA was no longer considered to be at low risk. Therefore, this is consistent with the view that different perceptions of expected loss can modify risk estimation. Because different panel groups were used for different regions, we may also consider the hypothesis that differences between study cases may in part be due to differences in the overall risk perception among group panels. Nevertheless, overall results were generally very consistent among groups, and there was little difference between panel groups in their perception of risk. However, an initial meeting involving expert leaders from all the regions for a preliminary standardization of the way to characterize the FMAs, select the main hazards, and run the scoring may have reduced variation in terms of attitude toward risks. Moreover, all experts belonged to the same sociological group (ecological scientists), thus possibly resulting in a high level of consensus. Therefore, the influence of risk aversion in MCRA should be further investigated by involving different panels of experts, including social scientists and forest end-users. We believe that our methodology, inspired by the MCDA approach, offers opportunities for such a follow-up study because decision-making software such as Decision Lab® is user friendly and allows testing via graphical outputs the effect of changing criteria and weight values.

In our MCRA, intensive even-aged forestry was consistently ranked as the FMA most at risk. This type of forest management combines three main features that may explain why it often leads to a high risk of biotic and abiotic damage. First, tree species are grown as pure stands, which are known to be more prone to pest insect, pathogen, game, and wildfire damage than mixed stands (Jactel and Brockerhoff 2007, Moreira et al. 2009). Second, the main objective of this type of forestry is to maximize tree growth in order to increase timber production within the optimal rotation length. Therefore, practices are designed to increase individual tree vigor, and include fertilizing to increase soil fertility, cleaning the understory, and thinning to reduce competition for light and water. However, vigorous trees are known to be more susceptible to primary pest insects, such as leaf chewers or aphids, and to primary pathogens, such as leaf rusts or stem cankers, as well as to mammal grazers (Price 1991, Gill 1992, Herms and Mattson 1992, Grodzki 2001). Because the latter biotic hazards are commonly the most frequent, they were more likely to be involved in our MCRA, thus exacerbating the estimates of susceptibility in intensively managed forests. In addition, even-aged forests are often regarded as being more susceptible to a number of abiotic threats, such as wind, snow, and ice damage, than uneven-aged stands, although the evidence is weak (e.g., Dhôte 2005). Conversely, vigorous trees are known to be more resistant to bark beetle attacks (Christiansen et al. 1987), due to their ability to produce more defense compounds, such as terpenes and phenols (Lieutier 2004). Some practices associated with intensive even-aged forestry, such as frequent thinnings (Fettig et al. 2007) can lead to lower susceptibility to bark beetles (e.g., Norway spruce stand susceptibility to *Ips typographus* in Austria,

Fig. 5. Ranking of FMAs according to impact on biological damage by main hazards (irrespective of forest stand values at stake), across eight different regional case studies (left-hand side) and for overall results (right-hand side).



Appendix 1) although such practices are also expected to increase the risk of windthrow, which can in turn trigger bark beetles outbreaks (Hanewinkel et al. 2011). Third, the goal of forest managers when applying intensive even-aged type management will be to maximize their profits, by attaching a high value to round wood. Any tree mortality or growth loss will then be considered to be critical, leading the experts to assign a high score of exposed value to damage. This seems to be consistent with the result that intensive even-aged forestry continued to be ranked the most at risk when greater weight was given to the consequences of tree mortality. In conclusion, the combination of high susceptibility due to a simplified stand structure and composition, large values at risk, and high relative frequency of primary pests and pathogens justifies the fact that intensive even-aged forestry was ranked as being at high risk of damage across all regions and tree species.

At the other end of the ranking, the wood biomass and close-to-nature alternatives were generally the FMAs with least risk of damage, but for different reasons. Close-to-nature management may be considered as the exact opposite of intensive even-aged management. Stands consist of tree species mixtures, no silvicultural operations are made to improve individual tree growth, thus leading to lower susceptibility, which is confirmed by the sensitivity test in which FMA ranking was made irrespective of exposed values and showed the best rank for close-to-nature forestry (Fig. 5). Furthermore, the main objective of this type of forestry is not to maximize wood production but to maintain continuous forest cover and biodiversity thus limiting the value at stake. This is consistent with the best rank obtained in the sensitivity test that gave lower weight to economical issues such as wood growth and quality. By combining low susceptibility and low exposed value, close-to-nature forestry should lead to a reduced risk of damage.

Forest stands in the wood biomass alternative are managed similarly to intensive even-aged forestry, to maximize tree growth and individual tree vigor. Therefore, they are likely to be equally susceptible to primary damaging agents, as shown by the sensitivity test that focused on this issue (Fig. 5). Because they are managed to maximize the production of wood biomass, they are highly vulnerable to damage that reduces growth loss and increases tree mortality, which explains the low ranking of this alternative in the sensitivity test that gave more weight to these two economic impacts (Fig. 4). In contrast, one of the main features of wood biomass forestry is the reduction of rotation length. Shortening the rotation length results in harvesting trees that have yet to be attacked by the most frequent forest pests and pathogens, and decreases the time that trees are sensitive to wind damage (Gardiner and Quine 2000, Dhôte 2005). Thus, harvesting trees when they are still young represents a good strategy to minimize the risk of wind damage but does not help in reducing fire risk as increased forest age results in lower vulnerability to fire in most European countries (Schelhaas et al. 2010).

The combined objectives FMA was always in the middle of the rankings. As this method of management was designed as a means of diversifying intensive even-aged forestry through integration of several silvicultural principles of the close-to-nature forestry, this outcome is logical.

The outcomes of the MCRA and sensitivity tests were highly consistent across the eight regional case studies. Although different panel groups participated in each studied region, they provided very consistent results, and we may consider it as an indication of a coherent evaluation of risk perception among them. However, the consistency may also have resulted from the choice of the case studies. We focused on a limited set of tree species grown in Europe that are mainly fast-growing species and on climatic areas favorable to tree growth, thus reducing the range of variation. The main discrepancy in the results of MCRA was observed with the eucalyptus forests in Portugal, for which the wood biomass alternative was considered equally at risk as the intensive even-aged alternative. In Portugal, the main hazards for eucalyptus stands are the snout weevil *Gonipterus scutellatus*, the psylid *Ctenarytaina spatulata*, and the leaf fungi *Mycosphaerella* spp. (Valente et al. 2008). All of them mainly affect young plantations (1–5 yrs old), reducing tree growth and wood biomass production. In this particular case, forest values are then more exposed in plantations managed for wood biomass production than in Intensively managed even-aged plantations.

This preliminary study has some limitations. First, the scoring of damage, susceptibility, exposed values, and occurrence of hazards was based on the knowledge of a single panel of experts per region. Because risk assessment also depends on risk aversion (Hanewinkel et al. 2011), which is a subjective matter, more panels should be consulted to provide a more robust ranking of FMAs. Second, our approach did not take into account the effect of large disturbances, such as storms or pest outbreaks, which may dramatically change the weight of some criteria (hazards). In any case, we do not expect that catastrophic events will affect our results in the sense of changing relative positions of different management options as they probably affect all forest management alternatives indiscriminately. Third, the aim of our analysis was to rank FMAs according to their impact on risk and not according to overall benefits. This study should be then considered only as a testing of the MCRA methodology, particularly its robustness, and not a recommendation of a particular FMA. In order to do that, more criteria (e.g., biodiversity, soil condition, timber, recreation) need to be included in the decision-making process (see other papers in this special issue).

Responses to this article can be read online at:
http://www.ecologyandsociety.org/issues/responses.php/4897

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APPENDIX 1.

Score of the effect of stand management options on relative susceptibility to biotic and abiotic hazards.

Aquitaine – *Pinus pinaster*

Action	Option	Hazards				
Close-to-Nature		**Defoliator**	**Stem borer**	**wind**	**fire**	**Root rot**
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	Stump destruction and harrowing for woody debris incorporation if a stand had 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	Ocasionally to ensure that the light/shade conditions are adequate to establish/maintain a mixed stand	1	0.75	0.75	1	1.25
thinning-pruning	Ocasionally to ensure that the light/shade conditions are adequate to establish/maintain a 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	Stump destruction and harrowing for woody debris incorporation if a stand had 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: spacing of 4m x 2m (final density ~1200 trees/ha)Beating up: 6 months after planting to replace dead trees (15%)	1.25	1.25	1	1	1
cleaning	Mechanical weed control (mechanical fertilization and weed control are done at the same time in a single operation)	1	1	1	0.75	0.75
thinning-pruning	If necessary, thinning after insects or fungi attacks also after intense night frosts and/or 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	Stump destruction and harrowing for woody debris incorporation if a stand had 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 Wuerttemberg – *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	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	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	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 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 for each FMA.

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 for each FMA. We used 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 vulnerability to five main hazards in each case-study region and for each FMA

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