

Review

Adaptation to Climate Change in Forestry: A Multiple Correspondence Analysis (MCA)

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Abstract: We analyze economic perspectives of forest adaptation to risk attributes, caused mostly by climate change. We construct a database with 89 systematically chosen articles, dealing simultaneously with climate, adaptation, risk and economy. We classify the database with regard to 18 variables bearing on the characteristics of the paper, the description of the risk and the adaptation strategy, the topic and the corresponding results. To achieve a “high level-of-evidence”, we realize a multiple correspondence analysis (MCA) to identify which variables were found in combination with one other in the literature and make distinct groupings affecting adaptive decisions. We identify three groups: (i) profit and production; (ii) microeconomic risk-handling; and (iii) decision and behavior. The first group includes economic costs and benefits as the driver of adaptation and prioritizes simulation, and a mix of theoretical and empirical economic approach. The second group distinctly involves risk-related issues, in particular its management by adaptation. The third group gathers a large set of social and behavioral variables affecting management decisions collected through questionnaires. Such an approach allows the identification of gaps in the literature, concerning the impact of owners’ preferences towards risk and uncertainty regarding adaptation decisions, the fact that adaptation was often reduced in an attempt to adapt to the increasing risk of wildfire, or the existence of a regional bias.

Keywords: adaptation strategies; climate change; risk; economics

1. Introduction

Talking about climate change implies dealing with mitigation and adaptation. Mitigation refers to “policies to reduce GHG emissions and enhance sinks” [1], while adaptation is defined as “adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities” [1]. For a long time, the scientific community focused mainly on mitigation to climate change. Speaking about adaptation to climate change was “politically incorrect” because it implied the acceptance of defeat in the battle against greenhouse gas (GHG) emissions [2]. However, thinking on the subject evolved, partly due to the acceptance that climate change may not be avoided [3,4], that ecosystems alone cannot succeed to adapt to the predicted changes [5,6] and that the impacts of climate change may be modified by adaptation measures [7]. Some evidence of this evolution is, for example, the introduction of adaptation into the international climate-change dialogue (agenda of the United Nations Framework Convention on Climate Change (UNFCCC), Conference of the Parties (COP) 10, COP 11), and the first consensual

definition of adaptation proposed in the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) in 2001.

Adaptation is required at all levels of society, from the industrial adaptation of building codes, to the agricultural development of drought-tolerant crops and also in forestry for the selection of tree species, as well as forestry practices which are less vulnerable to climate change. Forest ecosystems are also sensitive to climate change through increasing temperature, changes in precipitation regime and the rise in frequency and intensity of natural events (“adaptation for forests”). In addition, forests impact climate change because wood is a recyclable and ecological material, and because of their carbon storage capacity, among other reasons (“forests for adaptation”). Moreover, forest ecosystems are characterized by long-term decision-making because the management of most tree species usually encompasses several decades and is characterized by a quasi-irreversibility of decisions. These characteristics stress the necessity to study adaptation in a forestry context.

As a consequence, a huge literature has recently emerged on forest adaptation to climate change, with various approaches coming from ecology (spatial distribution, migration, etc.), biology (genotype, climatic scenario, etc.) and economy (individual behaviors, comparison of strategies, etc.), among others. A recent paper reviews the literature on climate-change impacts on forests and adaptation options for forest management [6]. It showed that only 130 of the 1172 collected papers focused on forest adaptation. It concluded that most of the papers published on forest adaptation to climate change dealt with vulnerability and impacts, while managers need greater guidance concerning management responses. Another review surveyed the approaches and models suitable for handling risk and uncertainty in adaptive forest management [8]. The article showed that most studies focusing on changing risks in forest management under climate change tend to build on existing approaches about changes in risk levels contingent on climate-change scenarios. In addition a number of other reviews have been carried out with various points of focus on overall the climate-change adaptation topic. For example, some reviews focused purely on the subject of adaptation [9,10], others dealt with adaptation and mitigation strategies [11] or planning, decision-making and trade-offs [12–15]. Other papers tackled climate-change impacts and vulnerability on forests [13,16–18], adaptation and uncertainty [19] and implementation of adaptation measures [20]. Finally, a last review dealt with sustainability and resilience in the adaptation context [21].

To our knowledge, there is currently no quantitative analysis of the literature focusing only on forest adaptation to climate change, while adopting an economic perspective, which is of particular importance. On the one hand, climate change will have an effect on the forest sector and timber market through impacts on productivity and growth. The expected economic impacts of climate change on industrial forestry have been highlighted through indicators such as wood price, producer and consumer welfare, and demand satisfaction [22]. On the other hand, forest owners susceptible to adopt adaptation strategies are economic agents and, therefore, a better understanding of their behaviors and decision-making process is necessary to implement relevant adaptation strategies. Economic approaches seem, then, to be of particular interest in tackling the challenge of forest adaptation.

In this context, we conduct a meta-analysis of the literature on the economics of forest adaptation to climate change. The general objective of the paper is to synthesize the existing literature on the adaptation of forestry to climate change, tackled from an economics perspective. More specifically, our objectives are: (i) to identify combinations of variables that are frequently found in combination in the literature, in order to observe groups of variables affecting adaptive decisions; (ii) to identify gaps in the literature in order to stress relevant research directions in the future. For that purpose, we provide a quantitative analysis and categorization of 89 published articles. We classify them with regard to 18 variables bearing on the characteristics of the paper (year, journal), the description of the risk (biotic/abiotic) and the adaptation strategy (planned/reactive), the topic and the corresponding results (risk management, risk perception, risk assessment, impact of risk). We propose an original statistical approach based on multiple correspondence analysis (MCA) to identify which categories

were often found in combination with each other in the literature and, in turn, where gaps in the literature may exist.

This paper leads to the current frontier in the understanding of the economy of adaptive forest management under climate change in several ways. Firstly, it amalgamates and analyzes relevant forest economics literature on adaptation to climate change and thereby improves the current state of knowledge on forest economics. In addition, by clearly identifying gaps in the literature, the manuscript indicates where future research efforts should be concentrated. Finally, the topic of adaptation to climate change is at the heart of forestry research and this paper stresses how an abundant economics literature on this specific topic is lacking.

2. Materials and Methods

2.1. Definitions

As indicated in the introduction, adaptation is an adjustment in response to climate change [1]. Based on this definition, forest owners and managers have many adaptation options. Taking the example of warmer annual and drier summer conditions on tree growth in southern British Columbia, several current adaptation actions have been indicated by Ref. [9]: identify more suitable genotypes through provenance trials, develop technology to use altered wood quality and size, include climate variables in growth and yield models, develop “fire-smart” landscapes; and future adaptation actions: modify seed-transfer zones, plant alternate genotype or new species, sanitation thinning, increase amount of salvage logging, change rotation length, plan landscapes to minimize spread of insects and diseases. Other adaptation strategies appear in the literature, examples include a shift from monocultures to mixed stands [23].

Different categorizations of adaptation strategies exist in the literature: proactive vs reactive adaptation [12], forward-looking vs trend-adaptive [24], active vs passive [13], planned vs reactive adaptation [25], etc. In this paper, we refer to this last categorization. Planned adaptation means to redefine forestry goals and silvicultural practices in advance in view of climate change-related risks and uncertainties; while reactive adaptation is a response to already observed climate-change impacts. Examples of planned adaptation are mixed-stands, plantation of more resistant tree species and reduction of rotation length; while examples of reactive adaptation are salvage cutting, post-disturbance changes in industrial processes to convert salvaged timber and updated harvest scheduling.

These adaptation options have been analyzed through a variety of disciplines, including economics. In the context of this meta-analysis, economic methods refer to economic calculation, econometrics, optimization, simulation as well as approaches based on surveys, interviews, and questionnaires.

2.2. Data

Our strategy to collect articles was based on two main methods.

In the first method, we conducted a literature research using the search engines Google Scholar and Web of Knowledge. Each research combined four types of keywords as follows:

- **Climat** * (*Climate, Climate change, Climatic*) OR **Adapt** * (*Adaptation, Adaptive*)
- **Forest** * (*Forest, Forestry, Forest management, Forest owner*)
- **Risk** * (*Risk, Risk perception, Risk management, Risk attitude*)
- **Econo** * (*Economics, Economy*)

In the second method, we used the bibliographies of the collected papers to add relevant articles to our database. Those papers whose bibliographies were used as an additional source of literature were Refs. [6,8,26].

The search was restricted to articles published in English. We thus collected and used 89 papers in our analysis (see the supplementary material for an exhaustive list of the bibliographical references).

We classified the content of these papers into 18 variables with 3 possible modalities, with four sets of variables. The choice of the variables and associated modalities emerges from a thorough investigation of each paper's content.

Firstly, we collected information about the characteristics of the paper like the *Methodology* (economic analysis; literature review, qualitative approach and survey; or simulation) and the *Objective* of the paper (economic profit, ecological sustainability, or socio-political dimension). For example, papers dealing with the impact of adaptation strategies on productivity or forest yield are classified as *Economic Profit*, those focusing on the impact in terms of biodiversity or species distribution as *Ecological Sustainability*, and articles about institutional and policy dimension of forest adaptation are categorized as *Socio-political*. Where there was more than one objective in a given paper, it was decided as to the classification of the principal objective of the paper. We also included a variable indicating if the paper was theoretical, empirical or both (*Theoretical/Empirical/Complex*). We defined *Population* as forest managers and academics or forest owners. For some variables, modality 3 is a "blank option" because the considered variable was not relevant for all papers. The variable *Population* is an example. Indeed, *Population* does not apply to all papers but only for those in modality 2 of the variable *Methodology*, so that a blank option (mod. 3) was specified.

Secondly, we collected information regarding the description of risk and adaptation. In this case, the variable *Risk type* indicated if the risk drew on ecological, economical or socio-political aspects. For *Climate Change* we considered temperature or precipitation level as causal factors. *Abiotic* damage was considered to come from wind, snow and storm or fire, while *Biotic* damage resulted from fungi and disease or invasive species, pest and insects. *Adaptation type* was planned, reactive or business-as-usual.

The third set of variables concerned the topic of the article. The variable *Category* was composed of three modalities: *Risk assessment and impact*, *Risk management*, and *Risk perception*. Four different sub-categories were also defined: *Impact of risk* (on production, probability, growth or damage), *Risk assessment* (probability of occurrence, damage/distribution), *Risk management* (prevention/insurance or silvicultural management), *Risk perception* (about climate-change or management options).

The last set of variables was related to the results. Four variables characterized the results and for each of them we included three modalities. Then, we determined whether the results are classified as: (i) *Economic profit/loss* with results on cost, benefit, yield, etc.; (ii) *Perception/Social attitude* with a focus on perception of risk, uncertainty, beliefs, etc.; (iii) *Ecological impacts* when outputs are related to identification of vulnerabilities, biotic shifts, scale effect, etc.; (iv) *Assessment/Vulnerability* with results on implementation of adaptation, mitigation, potential barriers, etc.

We also collected additional information concerning the name of authors, journal in which the paper had been published, the year of publication and the country/region in which the study took place.

2.3. Statistical Analysis

Our dataset consisted solely of non-linear nominal variables with more than two modalities and therefore a multiple correspondence analysis was conducted [27], which enabled the determination of combinations of variables and modalities which were most represented in our meta-analysis. The outputs of an MCA are eigenvalues (or inertias) and percentage of inertia (or explained variance) for each relevant combination of variables and modalities, called dimensions.

There are two main methods for carrying out the MCA, one involves the use of an indicator matrix and the other of a Burt matrix, obtained from an initial indicator matrix. Our MCA was carried out using an adjusted Burt matrix method, as it provided the best explanation of the variation in our data [28,29]. The analysis was carried out using the R statistical software with the package "ca" [20].

2.3.1. Indicator Matrix

MCA is used to analyze a set of observations described by a set of non-linear nominal variables. Each nominal variable comprises several modalities, and each of these modalities is coded as a binary variable. There are K nominal variables, each nominal variable has J_K modalities and the sum of the J_K is equal to J . There are I observations and the $I \times J$ indicator matrix is denoted as X .

Our dataset consisted of 18 nominal variables ($K = 18$) comprising 3 modalities ($J_K = 3$; $J = 54$). The number of observations is equal to 89 articles. The columns represent the variables (and modalities) while articles are expressed in rows. The indicator matrix X is then a matrix 89×54 , i.e., 4806 cells containing either 0 or 1.

An MCA may be performed on this indicator matrix. However, in our case a Burt matrix MCA was conducted because the eigenvalues obtained from this analysis provides an optimized approximation of the inertia of the eigenvalues of X by rescaling the Burt matrix solution [29,30].

2.3.2. Burt Matrix

The $J \times J$ table obtained as $X^T X$ is the Burt matrix associated to X . The Burt matrix is composed of all the two-way cross-tabulations of the set of variables being analyzed. In our case the Burt matrix is a 18×3 symmetric block matrix with 54 sub-tables. The diagonal sub-tables are cross-tabulations of each variable with itself, which is a diagonal matrix with the marginal frequencies of the variable down the diagonal.

An MCA can also be performed on this Burt matrix, however in the interest of achieving a higher level of explained variance by the given dimensions, i.e., the so called “percentage of inertia problem”, an “Adjusted MCA” was conducted. Indeed, adjusted MCA was used to compensate for the typical underestimation of the first dimension which commonly occurs in an MCA [28,29].

2.3.3. Adjusted Multiple Correspondence Analysis (MCA)

The “Adjusted” MCA increases the percentages of the explained variation in our modalities than would be explained through a standard Burt-matrix method. For our adjusted MCA, the following inequality and Formula (1) were used to make the adjustment for each individual inertia to reflect its contribution to the total explained inertia [28]:

$$\lambda_s^{\text{adj}} = \left(\frac{Q}{Q-1} \right)^2 \left(\lambda_s - \frac{1}{Q} \right)^2 \quad (1)$$

Formula (1) for the adjustment of individual eigenvalues and where λ_s = single explained inertia value, Q = number of variables.

This formula applies to those eigenvalues which satisfy the inequality $\lambda_s \leq 1/Q$ where λ_s is the single explained eigenvalue and Q is the number of variables [18]. The eigenvalue can also be expressed as a percentage of explained variation. A deviation coefficient superior to 0.3 indicates a strong correlation, according to the measure of the relationship between nominal values in Ref. [31], and was determined as the threshold to which enough of the variance was deemed to have been explained to continue the analysis. This was calculated by summing the eigenvalues and finding their square root. The correlation value, based on our data, was 0.348.

The dimensions quantified using MCA represent combinations of multiple variables and modalities as a method of reducing the information in our dataset to a simpler form for ease of interpretation. One dimension is constructed from the explained variation of the variable combinations used in the analysis, with their position relative to the axis being based on their level of correlation with that axis. The number of dimensions for our statistical analysis was chosen by finding the point of inflection from the scree plot of the eigenvalues (see Figure A1 and Table A1 in Appendix A) generated from the MCA [32]. Our analysis detected a point of inflection including three dimensions, explaining 72.6% of the variance in the MCA.

Regarding the contribution of each modality to the total variance in a given dimension, a value above the average contribution was considered to be the minimum threshold for further interpretation [33]. In our case this was any modality which had an average contribution of >1.8% (see Table A2 in Appendix B). Any single modalities which were not clustered with other values were also removed. Consequently, we retained 16 of 54 potential combinations (18 variables \times 3 modalities), described in Table A2 in Appendix B. The output of the MCA, i.e., the column co-ordinates generated from the adjusted Burt table, were then used as xyz co-ordinates, based on the three generated dimensions, which could then be displayed in a 3-dimensional graph. In our analysis, for ease of graphical interpretation, only those modalities which contributed to more than 4% of the total variance of each dimension were plotted, using the R package “Scatterplot3d” (i.e., 16 combinations).

3. Results

3.1. Descriptive Statistics

The papers collected were published in 33 different journals. “Forest Policy and Economics”, “Forest Ecology and Management” and “Climatic Change” gather approximately 30% of our sample. The selected papers range from 1989 to 2015, with an increasing trend over time, confirming that economic concerns about forest adaptation to climate change are a recent development. The papers cover the five continents. In our sample, 71 papers focus on developed countries and 6 on developing ones; while 12 are not geographically localized or have a global focus. We also observe that approximately half of the papers focus on Europe with some well-represented countries such as Sweden (11 papers), Germany (9 papers), Switzerland and Austria (3 papers each). North America is the second continent in terms of number of articles.

Table A3 in Appendix C presents the variables and associated modalities, and also indicates the frequencies (N) in each modality. Therein, several trends may be observed.

First, concerning the characteristics of the papers, we observe that in terms of *Methodology*, 71.9% of our sample is composed of *Literature review/Qualitative/Survey*. Concerning the *Objective*, the modality *Socio-political* aspects represent almost 60% of the sample. In addition, theoretical papers dominate in the sample. Among the papers, involving a sample of individuals (variable *Population*), 58% focus on *Forest managers/Academics*.

Second, the *Risk type* considered in the papers is *Ecological* (40.4% of the sample), *Economical* (34.8%) or *Socio-political* (24.7%). Approximately one third of the papers begin by indicating that *Climate change* will have a serious impact on forest ecosystem through increase in *Temperature*. The variable *Abiotic* is mainly driven by *Wind/Snow/Storm* with 30.3% of the sample while *Fire* represented 22.5%; and *Biotic*, largely dominated by *Invasive/Pest/Insect* with 39.3% of the sample. Concerning *Adaptation type*, *Planned* represents more than half of the sample (52.8%) and *Reactive* corresponds to 21.3%.

Third, the variable *Category* is well balanced in terms of proportion with 37.1% of the paper dealing with *Risk assessment and impact*, 37.1% with *Risk management* and 25.78% with *Risk perception*. This result is different from Ref. [6] who indicated that most of the papers he obtained focus on impacts, while managers need management responses.

Fourth, among the results, the modality *Adaptation/Mitigation/Barriers* for the variable *Assessment/Vulnerability* is substantially represented, with 29 papers among the 89 selected.

3.2. Dimensional Presentation of MCA

The 3D graph presented in Figure 1 plotted the 16 combinations (variable \times modality) retained for our analysis in relation to each of the three dimensions considered. This allowed an interpretation of the groups of modalities with a similar relationship to an individual dimension. The scale of each dimension was from -3 to $+3$, indicating negative and positive correlations to the relevant dimension respectively. Thus, we could identify which modalities were often found in combination with one other in the literature and in turn where gaps in the literature may exist.

On the basis of Figure 1, intra-dimensional and inter-dimensional results are presented below.

3.2.1. Intra-Dimensional Results

Figure 1 presents the three dimensions retained in our MCA. They may be interpreted as follows:

Dimension 1 can be summarized as “Profit and production”, since the most positively correlated variables of this Dimension 1 are *Economic Profit (Objective, mod. 1)*, *Cost-benefit/Yield (Result (Economic profit/loss), mod. 1)* and from the variable *Methodology* we have the modality *Simulation* and also the modality *Complex (Theoretical/Empirical/Complex, mod. 1)*. Consequently, this first group of variables includes economic costs and benefits as the driver of adaptation and prioritizes simulation, and a mix of theoretical and empirical economic approach.

Dimension 2 is entitled “Microeconomic risk handling” because the variables with a high positive correlation are *Risk management (Category, mod. 2)*, *Prevention/Insurance (Result (Risk management), mod. 1)* and *Forest owners (Population, mod. 1)*. This second group of variables distinctly involves risk-related issues, in particular management by adaptation.

Finally, Dimension 3 is “Decision and behavior”. Variables such as *Forest owners (Population, mod. 1)*, *Cost-benefit/Yield (Result (Economic profit/loss), mod. 1)*, *Risk perception (Category, mod. 3)* and *Empirical (Theoretical/Empirical/Complex, mod. 2)* have a high positive correlation to Dimension 3. This third group of variables gathers a large set of social and behavioral variables affecting management decisions collected through questionnaires.

3.2.2. Inter-Dimensional Results

Positive and negative correlations to each dimension were also identified. For example, *Fire (Abiotic, mod. 2)* is negatively correlated with each of the three dimensions, while *Forest owners (Population, mod. 2)* is positively correlated to Dimensions 2 and 3, and negatively correlated to Dimension 1.

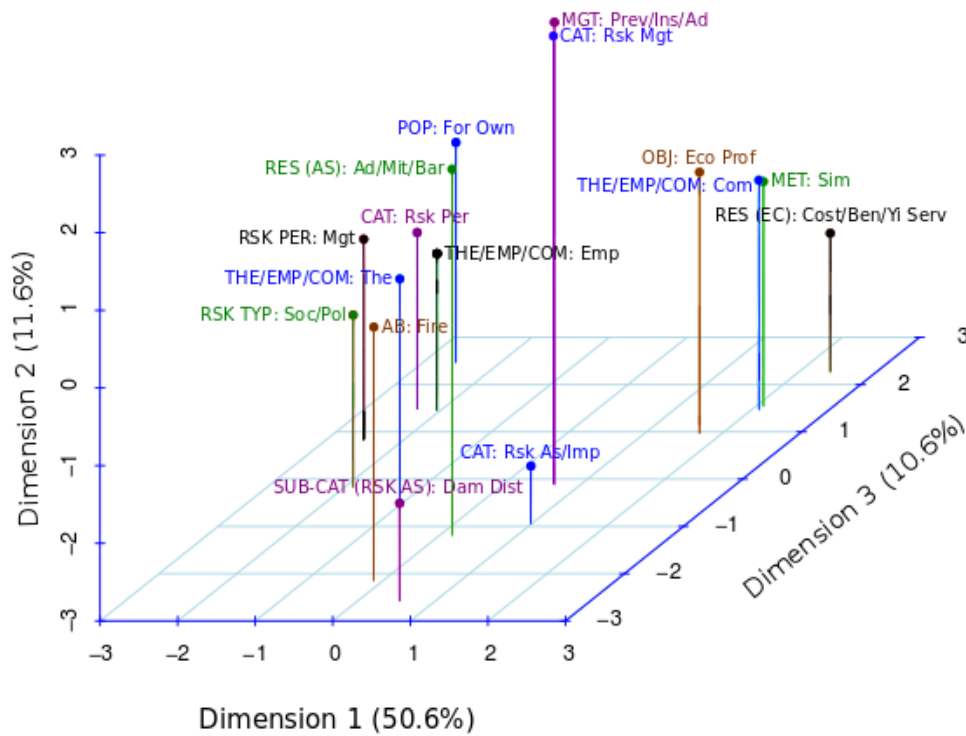
Following this idea, Figure 1 allows identification of three sets of variables and their correlation with each of the dimensions.

In the upper right part of the graph, we identify variables which are positively correlated with the three dimensions: *Economic profit (Objective, mod. 1)*, *Simulation (Methodology, mod. 3)*, *Cost-benefit/Yield (Result (Economic profit/Loss), mod. 1)*, *Complex (Theoretical/Empirical/Complex, mod. 1)*. This means that these four categories/variables often appear together in the literature.

In the upper left north-western part of the graph, the set contains variables that are positively correlated with Dimensions 2 and 3, and negatively with Dimension 1: *Socio-political (Risk type, mod. 3)*, *Management/Research (Result (Perception/Social attitude), mod. 2)*, *Risk perception (Category, mod. 3)*, *Empirical (Theoretical/Empirical/Complex, mod. 2)*, *Forest owners (Population, mod. 2)*. This means that the literature often deals with these different variables simultaneously.

The set located in the lower part of the graph is more heterogeneous. On the one side, variables like *Risk assessment and impact (Category, mod. 1)* and *Damage/Distribution (Sub-category (Risk assessment), mod. 2)* are negatively correlated with Dimensions 2 and 3, and positively with Dimension 1. On the other side, *Risk management (Category, mod. 2)*, *Prevention/Insurance (Result (Risk management), mod. 1)*, *Adaptation/Mitigation/Barriers (Result (Assessment/Vulnerability), mod. 2)* are positively correlated with Dimensions 1 and 2, and negatively with Dimension 3.

Note that *Fire (Abiotic, mod. 2)* and *Theoretical (Theoretical/Empirical/Complex, mod. 3)* are positively correlated with Dimension 2 and negatively with Dimensions 1 and 3.



(a)

Variable: Category	Code
Management: Prevention/Insurance/Adaptation	MGT: P/Ins/Ad
Category: Risk Management	CAT: Rsk Mgt
Population: Forest Owners	POP: For Ow
Result (Assessment): Adaptation/Mitigation/Barriers	RES (AS): Ad/Mit/Bar
Objective: Economic Profit	OBJ: Eco Prof
Theoretical/Empirical/Complex: Complex	THE/EMP/COM: Com
Method: Simulation	MET: Sim
Category: Risk Perceptions	CAT: Rsk Per
Result (Economic): Cost/Benefit/Yield services	RES (EC): Cost/Ben/Ye Serv
Risk Type: Societal/Policy	RSK TYP: Soc/Pol
Risk perception: Management	RSK PER: Mgt
Theoretical/Empirical/Complex: Empirical	THE/EMP/COM: Emp
Theoretical/Empirical/Complex: Theoretical	THE/EMP/COM: The
Abiotic: Fire	AB: Fire
Category: Risk assessment/Impacts	CAT: Rsk As/Imp
Sub-category (Risk Assessment): Damage Distribution	SUB-CAT (Rsk As): Dam Dist

(b)

Figure 1. Graphical representation of the results of the Multiple correspondence analysis (MCA). (a) Dimensional presentation of the 16 combinations of variables and modalities contributing to more than 4% of the total variance of each dimension; (b) The variables and their associated codes in the dimensional representation.

4. Discussion

This paper proposes a systematic quantitative review of the literature of the economics of adaptation to climate change, based on specific criteria and in a forestry context. A systematic review that achieves a high Level-of- Evidence (LoE) includes quantitative measures [34]. Therefore, we used an original statistical analysis, multiple correspondence analysis, displaying potential gaps in the literature. Three main gaps could be identified.

First, Dimension 3 indicates that while perception of risk is of interest in the literature, and more generally empirical behavior, it appears that the variable *Result (Perception/Social attitude)* and in particular modality 1 *Attitude/Perception of uncertainty/Updating beliefs* has a very low contribution to

the first dimension, which could explain the low contribution of the variable *Planned (Adaptation type, mod. 1)* in our study. However, for a long time, attitude towards risk is considered to be a main driver of forest-management decisions [35]. In addition, some recent papers highlight the role of the forest owner's attitude towards uncertainty [36,37]. Furthermore, uncertainties related to climate change are numerous with regard to the implications of climate change, alternative management, the timber market, and the expert advice provided by forest consultants [38]. The measurement of forest owner's preferences towards risk is very recent [39–41]. These papers utilized methodologies adapted from behavioral economics and proposed a quantification of the forest owner's parameter of risk aversion. They show that this parameter is important when dealing with timing in sales decision [40] and harvesting decision [40,41]. Such measurement under uncertainty for a population of forest owners has never been carried out. Consequently, the analysis of the role of risk aversion and uncertainty aversion on forest adaptation decision is still an open question, and represents a fundamental piece of information which could improve the understanding of the decision-maker's adaptation options and their likelihood of a planned, instead of reactive adaptation approach (probability to adapt, type of strategies implemented, timing of adaptation, etc.).

Second, some variables that seem to be important in dealing with adaptation in forests have a very low contribution to the total variance of a dimension. For example, the variable *Adaptation type: Planned (mod. 1)* has a percentage of explained variance between 0% (dimension 2) and 0.6% (dimension 1) and the higher percentage for *Adaptation type: Reactive (mod. 2)* is 3.6% (dimension 2). The same comment applies for *Climate Change: Temperature (mod. 1)* with percentages of explained variance belonging to the interval [0.5–3.1%] and the variable *Climate Change: Precipitation (mod. 2)* with an interval of [0–2.2%]. This would indicate that these variables have a very low contribution to the total variance of each dimension, suggesting a potential literature gap.

It can also be noted that only two variables always have a contribution lower than 1% in every dimension: *Abiotic: wind/storm* with a contribution going from 0 to 0.3%, and *Sub-category (Risk assessment): probability of occurrence* for which the interval is [0.1–0.6%].

Finally, one important conclusion of the inter-dimensional results is that the only *Biotic* or *Abiotic* risk mentioned in the MCA is *Fire (Abiotic, mod. 2)*, suggesting that adaptation of forest to climate change was often reduced to an attempt to adapt to the increasing risk of wildfire, while evidence of the impact of climate change on intensity and frequency of other natural disturbances are numerous in the literature. Future research should be oriented in this direction.

5. Conclusions

Two Other Findings Emerging from This Work

On the one hand, the descriptive statistics highlight that the scientific research about adaptation to climate change seems to focus on northern countries, despite the fact that it is the developing part of the world that is more vulnerable to climate-change impacts. This observation is in line with Ref. [42] who indicated that “the supply of climate-change knowledge is biased toward richer countries, which are more stable and less corrupt, have higher school enrolment and expenditures on research and development, emit more carbon and are less vulnerable to climate change”. Based on our review, we may infer that adaptive measures, given the lack of climate-change adaptation literature from developing countries, would tend to be reactive rather than planned.

On the other hand, our study indicates that papers explicitly taking into account price risk in relation to climate change are very few; only 8 articles evoke the timber price in their content. Some integrate the volatility in the model [43,44] while others question owners on their perception about price risk [45–47].

Supplementary Materials: The following supplementary materials are available online at www.mdpi.com/1999-4907/9/1/20/s1, Supplementary List of articles: Exhaustive list of the articles selected for the meta-analysis.

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Author Contributions: M.B.: systematic selection of the articles, supervision of the statistical works and writing of the article. R.B.: systematic selection of the articles, implementation of the statistical approach. M.H.: support in gathering relevant literature, support in conceptualizing the paper. R.Y.: support in gathering relevant literature, supervision of the statistical works.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

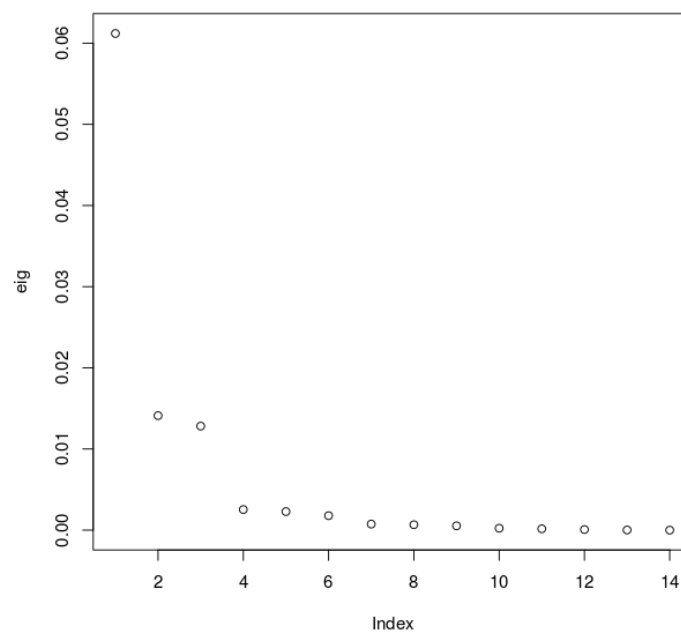


Figure A1. Scree plot of the eigenvalues calculated in our MCA. The y-axis shows the range in the values of our generated eigenvalues. The x-axis shows each dimension in order of the magnitude of its eigenvalue.

Table A1. List of dimensions, related eigenvalues, the dimensions’ explained variance and deviation.

Dimension No.	Eigenvalue	% Explained Variance	Cumulative Explained Variance %
1	0.061195	50.4	50.4
2	0.014111	11.6	62.1
3	0.01282	10.6	72.6
4	0.002538	2.1	74.7
5	0.002285	1.9	76.6
6	0.001785	1.5	78.1
7	0.000746	0.6	78.7
8	0.00067	0.6	79.3
9	0.000535	0.4	79.7
10	0.000239	0.2	79.9
11	0.000166	0.1	80
12	7.7×10^{-5}	0.1	80.1
13	2.2×10^{-5}	0	80.1
14	4.0×10^{-6}	0	80.1
Sum of eigenvalues	0.121305	-	-
Total explained deviation	0.348288	-	-

Appendix B

Table A2. % of explained variance in our MCA for our chosen combinations of variables and modalities and the mean explained variance of each dimension.

VARIABLE: Category	Dim1 %	Dim2 %	Dim3 %
RISK TYPE: Ecology	2.0	1.4	0.1
RISK TYPE: Economy	0.1	2.1	1.1
RISK TYPE: Sociology/Policy	4.9	0	0.9
ADAPT STRAT: Planned	0.6	0	0.1
ADAPT STRAT: Reactive	1.3	3.6	0.9
ADAPT STRAT: BAU/NA	0	3.1	0.2
CLIMATIC: Temperature	0.9	0.5	3.1
CLIMATIC: Precipitation	0	1.1	2.2
CLIMATIC: NA	0.4	0.1	2.6
ABIOTIC: Wind/Storm	0.1	0.3	0
ABIOTIC: Fire	0	5.7	0.1
ABIOTIC: NA	0.1	4.5	0
BIOTIC: Fungi/Disease	1.1	0.7	1.1
BIOTIC: Invasive/Insects	0.1	2.9	0.1
BIOTIC: NA	0.5	1.3	0.0
OBJECTIVE: Economic profit	4.0	1.3	0.2
OBJECTIVE: Ecological sustainability	1.5	0.1	1.5
OBJECTIVE: Socio-political	3.8	0.4	0.2
RESULT ECON: Cost-benefit/yield/services	4.7	4.2	1.2
RESULT ECON: Management goals and constraints	0.7	0.1	3.8
RESULT ECON: NA	2.6	0.7	0.6
RESULT PERCEPT: Perception of uncertainty and belief updating	3.0	0.3	0.0
RESULT PERCEPT: Perception of Management and research	1.9	0.1	0.3
RESULT PERCEPT: NA	3.9	0.3	0.0
RESULT IMPACT: ID of impacts	0.7	2.6	2.0
RESULT IMPACT: Impact distribution	2.4	1.0	1.2
RESULT IMPACT: NA	1.6	.3	2.0
RESULT ASSESS: Policy implementation	0.5	1.5	0.4
RESULT ASSESS: Adaptation measure and barriers	0	2.6	5.3
RESULT ASSESS: NA	0	3.1	2.2
TYPE: Complex	6.8	3.7	0
TYPE: Empirical	5.0	2.5	1.2
TYPE: Qualitative and theoretical	2	6.1	0.6
METHOD: Economical analysis	0.9	3.5	0.1
METHOD: Literature review/Qualitative/Survey	2.8	1.9	0
METHOD: Simulation	6.3	3.1	0
POPULATION: Forest managers and academics	2.0	0.9	0.1
POPULATION: Forest owners	5.8	5.3	0
POPULATION: NA	4.3	0.3	0.1
CATEGORY: Risk assessment and impacts	2.0	1.8	10.5
CATEGORY: Risk management	0.8	0	15.7
CATEGORY: Risk perception	7.8	3.2	0.8
SUB-CAT IMPACT: On productivity and growth	0.1	2.8	4.6
SUB-CAT IMPACT: Damage	0.3	2.4	0.1
SUB-CAT IMPACT: NA	0.1	1.1	0.8
SUB-CAT RISK ASS: Probability of occurrence	0.3	0.1	0.6
SUB-CAT RISK ASS: Distribution of damage	0.4	9.1	4.2
SUB-CAT RISK ASS: NA	0.2	2.9	1.9
SUB-CAT MANAGE: Prevention/Insurance	0.7	0	14.2
SUB-CAT MANAGE: Silvicultural management	0.1	0.1	2.9
SUB-CAT MANAGE: NA	0.4	0	7.6
SUB-CAT PERCEPT: Climate change and impacts	2.2	1.7	0.5
SUB-CAT PERCEPT: Management options	4.8	0.5	0.1
SUB-CAT PERCEPT: NA	2.0	0.6	0.2
Minimum dimensional contribution	1.8	1.8	1.8

Appendix C

Table A3. List of variables and modalities, and associated frequencies (N) in the database.

Variable	Modality 1	Modality 2	Modality 3
Characteristics of the paper			
Methodology	Economic analysis (N = 2)	Literature review/Qualitative/Survey (N = 64)	Simulation (N = 23)
Objective	Economic profit (N = 22)	Ecological sustainability (N = 15)	Socio-political (N = 52)
Theoretical/Empirical/Complex	Complex (N = 25)	Empirical (N = 19)	Theoretical (N = 45)
Population	Forest managers/Academics (N = 20)	Forest owners (N = 14)	NA (N = 55)
Description of the risk and adaptation			
Risk type	Ecological (N = 36)	Economical (N = 31)	Socio-political (N = 22)
Climate Change	Temperature (N = 30)	Precipitation (N = 3)	NA (N = 56)
Abiotic	Wind/Snow/Storm (N = 27)	Fire (N = 20)	NA (N = 42)
Biotic	Fungi/Disease (N = 7)	Invasive/Pest/Insect (N = 35)	NA (N = 47)
Adaptation type	Planned (N = 47)	Reactive (N = 19)	Business-as-usual (N = 23)
Topic			
Category	Risk assessment and impacts (N = 33)	Risk management (N = 33)	Risk perception (N = 23)
Sub-category (Impact of risk)	Production /Productivity/Growth (N = 14)	Damage (N = 3)	NA (N = 72)
Sub-category (Risk assessment)	Probability of occurrence (N = 3)	Damage/Distribution (N = 22)	NA (N = 64)
Sub-category (Risk management)	Prevention/Insurance (N = 26)	Silvicultural management (N = 2)	NA (N = 61)
Sub-category (Risk perception)	About climate change/Impacts (N = 8)	About management options (N = 12)	NA (N = 68)
Result			
Result (Economic profit/loss)	Cost-benefit/Yield (N = 13)	Management goal/Impact constraints (N = 23)	NA (N = 53)
Result (Perception/Social attitude)	Attitude/Perception of uncertainty/Updating beliefs (N = 31)	Management/Research (N = 9)	NA (N = 49)
Result (Ecological impacts)	Identification of vulnerabilities, impacts, disturbances, biotic shifts (N = 21)	Distribution/Scale/Assessment (N = 13)	NA (N = 55)
Result (Assessment/Vulnerability)	Political implementation of adaptation (N = 10)	Adaption/Mitigation/Barriers (N = 29)	NA (N = 50)

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