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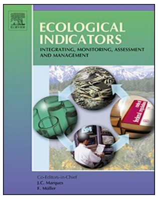

Original Articles

Spatial modelling approach to evaluate the economic impacts of climate change on forests at a local scale

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ABSTRACT

Global warming has caused significant environmental and socio-economic impacts on the global and local scales. Based on the definitions of vulnerability and resilience provided by the Intergovernmental Panel on Climate Change, some ecological and management indicators have been developed for forest systems. Using Dempster-Shafer's theory of evidence, forests were subdivided into different classes of vulnerability and resilience. Results enabled the estimation of economic damages to forests by 2050. The findings of this study are useful in promoting further research and guiding management decisions towards sustainable environmental policies on the monitoring and mitigation of climate change damage.

1. Introduction

The impact of humans on earth is inducing irreversible effects on the global and regional scales. The rise in GHGs has increased more rapidly over the last ten years than in the three previous decades (IPCC, 2014); projections actually indicate a 3.7 to 4.8 °C rise in the average temperature by the end of the century, in the absence of real mitigation strategies. Variations in atmospheric composition (Donat et al., 2013) and the reduced absorbing capacity of the major terrestrial sinks (Le Quéré et al., 2009) describe worrying scenarios both for humans and for natural systems. The large-scale extreme events (Hanley and Callabero, 2012), which have increased over the last few years, are all undeniable signs of climate abnormalities. The expected effects will involve changes in the distribution and density of habitats and species, both in space and over time (Maron et al., 2014).

At present, the extent of climate change impact varies from region to region. At the European level, the Mediterranean Basin is the most problematic area and it has long been identified as one of the major climate change hotspots, with harmful consequences on the productivity and reproducibility of agricultural and forest ecosystems (Bindi et al., 1996; Centritto, 2005; Maracchi et al., 2005; Stanisci et al., 2005; Moriondo and Bindi, 2007; Cannone et al., 2007, 2008; Sgobbi and Carraro, 2008; Orlandini et al., 2009). In particular, the impacts of climate change on the forest sector will increasingly be stronger but they will vary in the space and over time depending on the geographical region and the crop type (Thuiller et al., 2005; Dormann et al., 2008). As to the expected future scenarios for Europe, the response of forests to climate change will involve either a reduction of the forest capital, caused by a reduced water supply in the Mediterranean area (Giorgi and Lionello, 2008; Rajas et al., 2013), or an expansion of forests (in terms of areas and species) and an extended growing season for the north of Europe, as a result of the more favourable soil temperature and moisture conditions and the higher supply of carbon dioxide for photosynthesis (Paoletti, 2007). Rapid climate change actually induces modifications not only in environmental conditions but also in forest management objectives (Alley et al., 2003, Millar et al., 2007, Vicente-Serrano et al., 2012). It is thus necessary to draw special attention and take the appropriate adaptation and mitigation measures, via the planning and optimisation of efficient strategies to combat the effects induced by climate change while exploiting as much as possible the forest attenuation potential. In this context, climate simulation models can be very helpful to assess the potential effects on forest systems and to identify action strategies and management techniques aimed to improve their adaptive capacity. These models have a great potential but also some limitations related to uncertainties in information and to the effects and/or impacts on complex systems, like forests.

According to the IPCC *Assessment Report* AR5 (IPCC, 2013), the probabilistic estimates of quantitative measures of the uncertainty of a result are based on the statistical analysis of observations or on the results of models, or on both. Many authors have tried to overcome the limitations related to the uncertainty of simulation models: New and Hulme (2000) have proposed a probability-based approach to quantify

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Nomenclature

AHP	Analytic Hierarchy Process
AR5	Five Assessment Report
Bel	Belief
BPA	Basic Probability Assignment
C	Costs
CPL	Commercial Price at Landing
DEM	Digital Elevation Model
DS	Dempster - Shafer
FMP	Forest Management Plan
FO	Forest Owners
GHGs	Green House Gases
GIS	Geographic Information System
IPCC	Intergovernmental Panel on Climate Change
K_FO	cost charged to Forest Owners
K_LC	cost charged to the Logging Contractor
Kt	Total cost
LC	Logging Contractor
maIQt	mean annual Increment in quintal for each forest type
MWV	Marketable Wood Volume
PLS	Plausibility
R	Revenue
REA	Reliability Ensemble Averaging
RCMs	Regional Climate Models
RCP	Representative Concentration Pathways
SCI	Sites of Community Interest
SPZ	Special Protection Zones
SRES	Special Report on Emissions Scenarios
SV	Stumpage Value
TEV	Total Economic Value

the uncertainty of climate change; Raisanen and Palmer (2001) have developed a probabilistic approach to shape the intrinsic uncertainty of climate calculation representations; Giorgi and Mearns (2002, 2003) have worked out the REA methodology to estimate the probability of climate change on the regional scale by combining different simulation models; Tebaldi et al. (2004, 2005) have proposed the Bayesian approach to determine probability density functions of temperature variations from the results of various models; Wilby and Harris (2006) have developed a framework to assess the uncertainties of climate change impact on the Thames river, in the United Kingdom, and Ghosh and Mujumdar (2007) have used a nonparametric approach to model uncertainty in the assessment of drought, by incorporating climate change. Among the various methodologies applied to assess the uncertainty associated with climate change, evidence theory or DS theory (Shafer, 1976) is one of the best models for distinguishing the knowledge levels and managing the levels of uncertainty. DS theory has been applied to different research areas, ranging from hydrology (Nampak et al., 2014) to laser scanning and multispectral remote sensing systems (Saeidi et al., 2014). Some applications have also concerned the forest sector: Ducey (2001) presented a case of adaptive management forestry decision-making, in which he applied belief functions to produce not only optimal policy indications but also information about the level of certainty in decision-making; Yousefpour et al. (2012) have shown that climate variables (temperature and rainfall) have more influence than the measured forest variables on the management decisions for mitigating climate change impact. DS theory

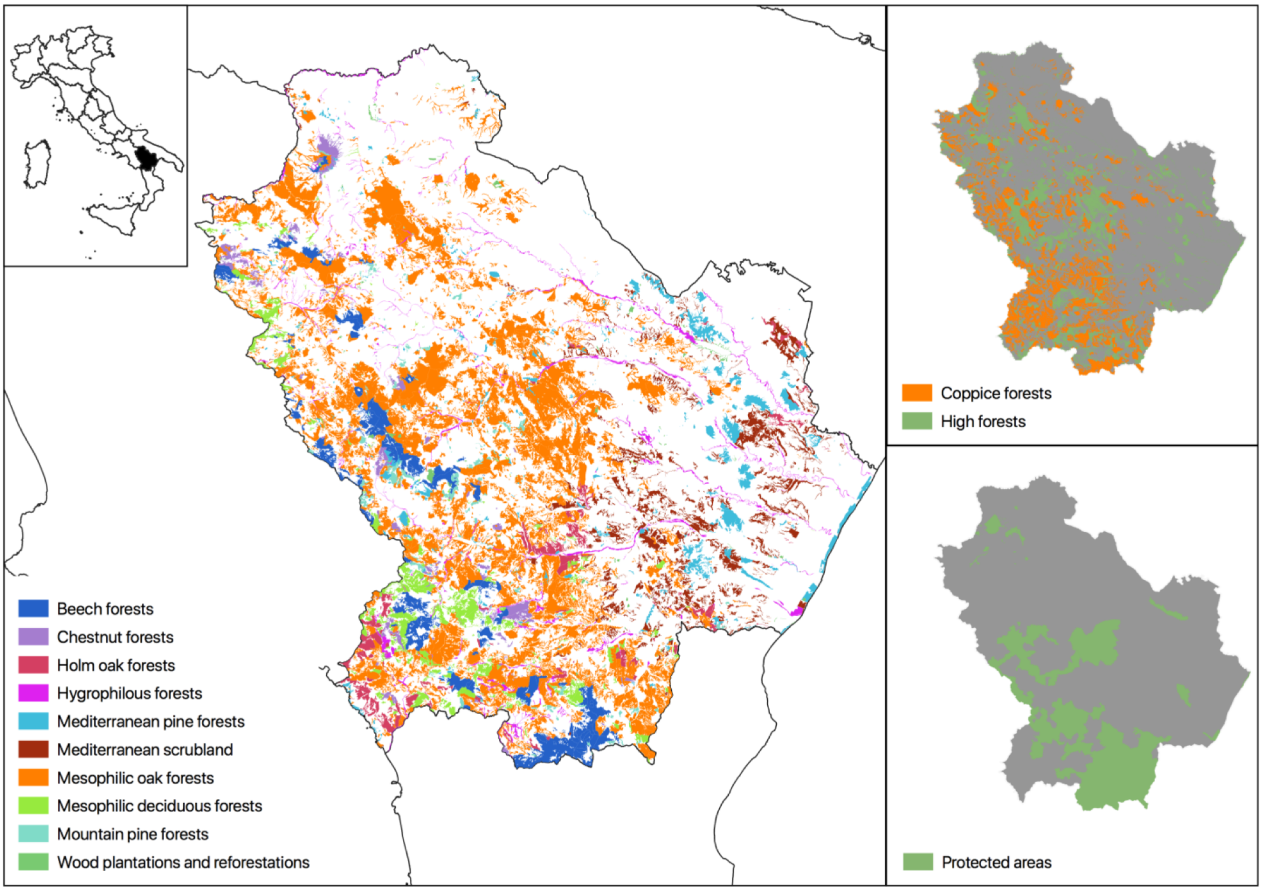

Fig. 1. Basilicata forests by type, management systems and protected areas.

has also been used to carry out the analysis of loss risk in complex systems: Deng et al. (2011) actually highlighted that the loss risk may be described by the sector experts using a linguistic approach based on *fuzzy* sets. The latter has been revived by Bernetti et al. (2011) who assessed the damage risk induced by climate change in Tuscany's forests, using a spatial analysis procedure.

Based on that and thanks to the local climate scenarios provided by the recent RCMs with high-resolution climate change projection maps (Jacob et al., 2014), the aim of the study is to assess the levels of vulnerability and resilience of forests, as well as the level of uncertainty, induced by climate change by using DS theory. This procedure enables the economic quantification of the loss of forest yield function. Starting from vulnerability and resilience values, it is possible to estimate the economic damage derived from the loss in biomass yield. The Basilicata region (Southern Italy) was selected as the pilot area for the application and rating of the model.

Estimates have concerned two time intervals corresponding to 2012 (as reference year) and 2050. Based on the results obtained, adaptive management strategies were proposed for reducing climate change impact.

2. Basilicata region case study

The study area was carried out in the Basilicata region, a rural area in the South of Italy, located between latitude 39°54′ N and 41°12′ N and longitude 15°21′ E and 16°51′ E (Fig. 1). The surface area of the region is 9995 km^2 with a population of 570,365 inhabitants (ISTAT, 2018), mostly rural territory with two thirds of the population concentrated in the few large urban towns.

In terms of climate there are differences specifically due to the complex orography of the region and its geographical position. The region is characterised by mountainous and hilly areas of the Apennine range (in the NW-SE direction), bounded by the limestone base of the Murge hills and the Bradano depression in the north-east, and by the Ionian coastal plains in the east. The elevation varies between 0 and 2200 m asl hence, while a large portion of the territory shows typically Mediterranean features (Ionian coast, Bradano depression and Murge hills), the areas above 800 m asl are characterized by a temperate-cool climate with quite dry summers. Average annual precipitation ranges from 529 till about 2000 mm, concentrated in the South-Western area of the region, as the Apennine range intercepts most of the Atlantic weather disturbance in the Mediterranean. The rainiest months are November and December, the driest are July and August, when severe droughts are frequent. The temperature is characterised by wide variations, with very hot summers and very cold winters. The coldest month is usually January (with an average temperature between 4 and 7 °C).

As every rural region, the study area is characterised by an agroforestry landscape. According to the last agricultural census (ISTAT 2010), the utilised agricultural area is equal to 519,127 ha, mostly dedicated to cereal cultivation on non-irrigated arable land (158,851 ha), followed by olive groves (31,351 ha), vegetable and orchards on permanently irrigated land (about 16,000 ha), and vineyards (5361 ha). The forests cover a surface of 354,895 ha (with an index of woodiness of 35.6%), consisting mainly of oak (51.8%), followed by beech (10%) and Mediterranean scrubland (7.9%) (Costantini et al., 2006) (Fig. 1). Coppice is the most widely used system of forest management (51.6%), representing 97.3% in chestnut, 59.2% in oak and 50% in beech principally widespread in private forests, while high-forest management is principally widespread in public ones. The goal is to give public forests a higher level of naturalness.

Given the high bio-ecological diversity of natural habitats and forests in the region, the protected natural areas of Basilicata cover about 30% of the entire regional surface (about 407,546 ha), with two national parks, two regional parks and six regional nature reserves. To preserve this diversity, it is necessary to understand the impact of climate change, not only for the environmental importance of forests, but also for the socio-economic one. Among the different ecosystem services provided by forests, the use of wood as an energy source plays an important role in the rural economy, contributing to diversify the renewable energy supply now and in the near future (Cozzi et al., 2013; Romano et al., 2013a). We have also to consider new uses of forests recorded in the region, that have positive impacts on income and employment, linked to tourist-recreational activities, sports, environmental education, enhancement of non-wood products and cultural services.

3. Methodology

3.1. The Dempster-Shafer's theory of evidence and normalisation

In the present study, the uncertainty related to the effects of climate change on the forest sector has been addressed using Dempster-Shafer's theory of evidence (Shafer 1976; Bernetti et al., 2011; Romano et al., 2015). DS theory offers a wide range of practical applications used in analysis under uncertainty conditions. It is based on the Bayesian concept but deviates from it with reference to the notion of plausible inference (Shafer, 1976). As a matter of fact, contrary to the Bayesian probability, DS theory allows two distinct values to express both the belief (Bel) of a given statement and its denial. Contrary to the Bayesian theory of probability, uncertainty is not automatically the complement of knowledge. Instead, it represents the degree of support for all assumptions. Interpreting this outcome, it is possible to state that, while belief Bel (h) constitutes the degree of concrete evidence to support an assumption - such as vulnerability - plausibility PLS (h) indicates the degree to which conditions seem to be appropriate for this assumption, although a supporting line of evidence is lacking or difficult to be attributed. Therefore, for each assumption Bel (h) is the lower limit of our commitment to this assumption and PLS (h) is the upper limit. The interval between the two represents the degree of uncertainty to establish either the occurrence or non-occurrence of this assumption.

Dempster-Shafer's theory of evidence is helpful to considerably reduce the range of uncertainty between two lines of evidence Vulnerability and Resilience (Romano et al., 2015), although the Bayesian concept represents the starting point of reasoning on plausibility in the DS theory. The common idea is that plausible reasoning is a form of uncertain reasoning based on sources that supply reliable rather than certain information. The notion of probability "p" in DS theory differs from the notion of Bayesian probability: given two assumptions A1 and A2, we have p(h) + p(s) + p(h, s) = 1 and therefore p(h) + p (s) < 1 in DS; whereas, according to the Bayesian approach, we have p (h) + p(s) = 1. The evaluation of assumptions is focused on the Basic Probability Assignment (BPA). The BPA is the contribution supplied by a factor (a_i) to support a specific assumption (such as resilience). The BPA assessment is based on the combination of fuzzy functions of environmental and socio-economic variables, evaluated by the Analytic Hierarchy Process (AHP) (Saaty, 1988), using the following formula:

$$BPA(a_i x) = \mu_{AHP}(a_i) \bullet \mu_{ai}(x_{ai}) \tag{1}$$

where: $\mu_{AHP}(a_i)$ is the AHP-based assessment of the confidence of the effect concerning the damage to forest stands in the hypothetical scenario of climate change with variable (a_i), and $\mu_{ai}(x_{ai})$ is the evaluation through a membership function of the hypothetical effects of variable a_i in space x. The aggregation for the assumption of vulnerability and resilience to climate change can be done in pairs, based on their joint probabilities (Shafer, 1976). For two BPAs ($a_i x$) and ($a_j x$) (for example: i = aridity and j = change in phytoclimatic zone) the orthogonal sum is:

$$BPA(a_i x, a_j x) = \frac{BPA(a_i x) * (1 - BPA))}{(1 - BPA(a_i x)) * BPA(a_j x)} \tag{2}$$

All factors are progressively aggregated in pairs to calculate the mass probability of vulnerability *m(h)* and mass probability of resilience *m(s)* (Bernetti et al., 2011). Once single BPAs are quantified, the DS technique proposes, thanks to the rule of the orthogonal sum, additional knowledge of the phenomenon *Bel(h)* and *Bel(s)* resulting from the masses of probability of single factors (Eq. (3)).

$$Bel(h) = \frac{m(h) * (1 - m(s))}{1 - m(h) * m(s)} \otimes Bel(s) = \frac{m(s) * (1 - m(h))}{1 - m(h) * m(s)} \tag{3}$$

Lastly, the aggregation of the two pieces of evidence *Bel(h)* and *Bel (s),* i.e. vulnerability and resilience, is done by normalising their respective joint probabilities that are not in conflict with each other. This also enables the determination of the intrinsic uncertainty, which shows where further research needs to be done in order to reduce the analysis uncertainty:

$$U(h, s) = Bel(s) - (1 - Bel(h)) = \frac{(1 - m(h)) * (1 - m(s))}{1 - m(s) * m(s)} \tag{4}$$

Applying the concepts of resilience and vulnerability to forests, the first step was the identification of a set of indicators for each line of evidence through the analysis of static and dynamic indicators (Tables 1 and 2).

Vulnerability is the degree to which a system is susceptible to, and unable to cope with adverse effects of climate change, including climate variability and extremes (IPCC, 2007). Since it is a function of character, magnitude, and rate of climate change as well as variation to which a system is exposed, its sensitivity and its adaptive capacity, we have chosen indicators linked to climate, territorial characteristics and biophysical conditions of forests (Table 1).

Resilience is defined as "*the ability of a system to absorb disturbances while retaining the same basic structure and ways of functioning, the capacity for self-organisation, and the capacity to adapt to stress and change"* (IPCC, 2007). It is basically a function with intrinsic characteristics of a system, whose adaptive capacities can however be influenced by human actions. Therefore, for the line of resilience evidence, we have chosen the index of variety as characteristic of forest ecosystems, and a set of indicators related to forest management methods (Table 2).

To be in line with the the SRES A1B climate scenario (IPCC, 2007), the climate data to 2050 was derived from climate projections of the Global Circulation Model-Regional Circulation Model ensemble CNRM-ALADIN5.3 for RCPs 8.5 scenario from the EURO-CORDEX project (Croce et al., 2018; Jacob et al., 2014). The forest data was derived from the Regional Forest Map provided by Costantini et al. (2006).

To harmonise the examined indicators, normalisation was carried out for quantitative indicators by using fuzzy function (Cozzi et al., 2014; Romano et al., 2013b), whereas fuzzy linguistic operators were used for the assessment of qualitative indicators (Chen and Hwang, 1992; Cozzi et al., 2015). In fact, the possibility of comparing different indicators, such as the change in phytoclimatic zones and the presence of managed areas, necessarily requires normalisation or a reclassification of criteria in a *range* of common values, where the lowest and highest values respectively correspond to the minimum and maximum probabilities that a factor contributes to the expression of the phenomenon (resilience or vulnerability). Linguistic quantifiers constitute a methodology that enables us to convert the qualitative opinions supplied by decision-making (that is the high influence of an indicator on a line of evidence, either "vulnerability or resilience") into a number, keeping the intrinsic uncertainty of the estimate. The applied conversion scale used in this study is scale 2, developed by Chen and Hwang (Chen and Hwang, 1992), where linguistic terms are converted in precise values: high 0.88, medium 0.5 and low 0.16 with the degree of risk-aversion equal to 0.52.

3.2. The economic component of the forest value

Forests may be qualified as a mixed asset that has elements of both public and private goods. The private component, which corresponds in most cases to wood production, involves the owner, whereas the positive externalities associated with forest stands (water runoff control, tourism, air quality, etc.) concern the public and/or collective component. More specifically, the economic value of environmentally-relevant goods, in particular forests, may include two categories of values, i.e. use and non-use values, which constitute the components of the TEV. For the monetary estimate of TEV, a number of methodologies have been proposed that are grouped as direct or indirect methods, although each of them shows application problems or some errors and uncertainty. Contrary to TEV, stumpage value, which concerns the yield potential of stands and, more specifically, wood production, is a well-

Table 1
Indicators for lines of vulnerability evidence for the forest sector.

Lines of evidence	Indicators	Description	Source data
Vulnerability	Aridity (de Martonne Index)	One of the main concerns of forest vulnerability (Allen et al., 2010), due to an increase in temperatures and a decrease in precipitation. The increase in drought conditions determines potential water stress with problems both at phytosanitary and pathological level. Heating also leads to the anticipation of vegetation period and, therefore, the increase in the risk of damage from spring frosts (Bernetti et al., 2010).	Regional map of the average annual precipitation and mean annual temperature in 2050.
	Vigour of forests	Health status of forest stands compared to the ability to effectively perform its functions (Costantini et al., 2006). The degree of vigour can also be defined as the ability to face disturbances: less vigorous stands will be more vulnerable to both biotic and abiotic variations.	Forest map. Data: Vigour.
	Change in Phytoclimatic zone	The phytoclimatic zones, defined according to the classification of Pavari (1959) (*Lauretum, Castanetum, Fagetum, Picetum*), are the most direct expressions of the relationship between forest vegetation and climate (Pignatti, 2011). A change in the distribution of phytoclimatic zones consequently affects the distribution of species related to them.	Regional map of the average annual temperature and average temperature of the coldest month in 2012 and 2050.
	Slope	Directly linked to tree stability, on higher slopes hydrogeological instability occurs more frequently, with possible landslides, in particular in the case of heavy rainfall (Bernetti et al., 2010).	DEM
	Aspect	Aspect influences forest vulnerability in terms of different microclimatic conditions, that may affect the entry into vegetation period (and therefore the risk related to late frosts), and environmental conditions favourable or not to phytophagous insects. It has been found that Southern exposures are the most vulnerable regarding the two previous aspects (Bernetti et al., 2010)	DEM

DEM: Digital elevation model

Table 2
Indicators for lines of resilience evidence for the forest sector.

Lines of evidence	Indicators	Description	Source data
Resilience	Managed forest	Percentage of public forests with FMP, cutting planes, and improvement. The management of forest stands makes it possible to guarantee the safeguarding of forest ecosystem services (Millar et al., 2007). The planted stands and stands with phytosanitary problems, represent the examples in which appropriate silvicultural and utilization interventions can guarantee the increase in forest resilience.	Regional map of FMP processed
	Accessibility	Degree of accessibility, meaning the distance from main, secondary roads and trails. The road network is one of the aspects that should not be underestimated to increase the resilience of a forest (Millar et al., 2007). A high degree of accessibility, for example, facilitates management actions, as well as fire prevention and surveillance.	Regional map of the road network
	Protected areas	Forest areas in national and regional parks, SCI / SPZ. In protected areas, the presence of regulatory and economic instruments for the protection, improvement and conservation of nature reserves allow to increase forest resilience to possible climate change.	Regional map of protected areas
	Management system	Forests classified according to the management system: coppice, coppice in conversion to high forest, high forests. The different management systems influence the adaptability of forest stands differently, affecting forest structure and composition (Bottalico et al., 2016)	Forest map. Data: Third level.
	Index of Variety	Defines forests according to the degree of variety of species. The increase in ecological and structural variables linked to the diversity of tree species greatly increases the ability of an ecosystem to resist external disturbances, as in the case of climate change.	Forest map. Data: Naturalness (low; medium; high) / ha of woodland.

established evidence whose theoretical roots are found in the works by Serpieri (1917), Patrone (1947), Cantiani (1957), Merlo (1991) and more recently Bernetti and Romano (2007).

SV is the value of the cut timber at a centre (e.g. landing area) minus the costs of logging and delivery. Its calculation is based on the partial balance of the production cycle, including revenue (*R*) on one side, and costs (*C*), on the other:

$$SV = \sum R - \sum C \tag{5}$$

The calculation of the revenue (*R*) is based on the marketable wood volume (*MWV*) and the commercial price at landing (*CPL*). In formal terms we have:

$$R = [MWV \bullet CPL] = \sum_{i=1}^{n} CPL_i \bullet Q_i \tag{6}$$

where *Q* is the volume in m^3 obtained from forest surveys or based on tree volume tables, and *n* the different types of obtainable assortments.

As for the balance liabilities, the costs of forest owners (FO) are separated from those of the logging contractor (LC), and the production cycle is split into different steps. In general, total production costs are obtained as follows:

$$Kt = \left(\sum_{i=1}^{4} K\_FO_i\right) + \left(\sum_{i=1}^{4} K\_LC_i\right) \tag{7}$$

where *Kt* is the total cost of the production cycle, *K_FO* the cost charged to forest owners, *K_LC* the cost charged to the logging contractor and $i = 1, 4$ steps of the production cycle.

Forest owners' costs include the costs concerning the administrative procedures and the charges associated with the remuneration of the forestry professionals. The main costs for the LC are mostly concentrated in the implementing phase, including the stand technological cycle. They may be classified as operating (or direct) and general (or indirect) costs. Operating costs concern the cost of labour and the running cost of machines. Whereas, general or overhead costs include the costs for management and surveillance; they reflect the activity related to the coordination of the business production factors in the construction site and the surveillance of the site and its products. They often include implicit cost items, calculated on a percent basis in relation to the other cost items.

More specifically, SV in 2012 (reference year of the analysis) was calculated using the *GIS* application, where each territorial unit was attributed each single cost and benefit item based on its location.

The wood mass was quantified using the wood volume tables for Basilicata region. Therefore, the values of mean annual increase were used and grouped according to the locally existing forest types and management systems.

The value of assortments is determined by technological features of the wood and final usage. Market surveys conducted among businesses and local mediators and retailers pointed out that the assortments obtained from forest stands are usually sold on a weight basis (q). Over 80% of wood is used for energy purposes, whereas the remaining 20% is used for posts or low quality lumber, with prices not very dissimilar from those of firewood. Based on that, the analysis was carried out considering the whole growth as firewood. The trading costs of assortments to the landing were deduced from the cut projects drawn for the forests of the region (Table 3).

For the balance liabilities, costs were distinguished on the basis of silviculture operations. More specifically, for cutting and lumbering the working site was assumed to include a specialised worker and two skilled workers with a chainsaw used for 8 h/day and a mean yield of 15 m^3/day. For the costs of labour, reference was made to the average unit price paid by the locally operating businesses, and estimated to 11 €/m^3.

For hauling operations, the working site was assumed to include two skilled workers and a specialized one, equipped with a forest tractor and pulley. Wood is piled up at the landing, close to the road for heavy vehicles. For this cost item, reference was made to the functions reported by Cozzi et al. (2013).

Management, running and surveillance costs were assessed - on a percent basis - on cutting and hauling costs and were estimated to be 15% of the latter, whereas other design and testing costs were calculated as 10% of utilisation costs.

The values relating to cost items were harmonized to have a quintal-based value, and multiplied by the mean annual increase per hectare. The latter was thus related to the reference territorial unit (*pixel* of 20 m per side, corresponding to an area of 400 m^2). The result obtained was the mean annual increase of the *pixel* for each forest type ($maIQ_t$)

Table 3
Firewood prices at landing.

Forest type	Assortment woody	Market price at the landing road (€/q)
Oak forests	firewood	5.50
Beech forests	firewood	5.00
Mediterranean pine forests	Energy use	4.00
Mountain pine forests	Energy use	4.00
Hygrophilous forests	Energy use	4.00
Wood Plantations and Reforestations	Energy use	4.00

Table 4
Mean annual increment q/pixel by forest type and management system.

Forest Type	Mean annual increase	
	High Forest (q/pixel)	Coppice (q/pixel)
Oak forests	1.11	2.64
Beech forests	1.42	1.47
Mediterranean pine forests	2.34	–
Mountain pine forests	1.99	–
Hygrophilous forests	1.72	1.23
Wood Plantations and Reforestations	0.69	–

(Table 4).

The difference between the price of assortments (R) at the landing and the sum of cost items (ΣC) multiplied by the mean annual increments in quintals ($maIQ_t$) results in the annual stumpage value (SV_i) of the i-th *pixel:*

$$SV_i = (\mathrm{R} - \sum \mathrm{C}) * maIQ_t \tag{8}$$

The results in 2012, once spatialized, have enabled the implementation of the model for the assessment of the economic damage for the scenario subsequent to 2050, via the accumulation of the mean increments per hectare:

$$SV_{2050} = SV_{2012} + \sum_{i=1}^{38} SVmaIQ \tag{9}$$

The next step was to calculate the stumpage values concerning each forest type in 2050 according to the SRES A1B scenario of IPCC including the levels of *Belief h* (vulnerability) estimated through DS theory of evidence:

$$SV\_v_{2050} = SV_{2050} * [1 - Belief\,(h)] \tag{10}$$

The analysis concerned only the time step to 2050 due to the difficulties of quantifying the discount rate[1] for time intervals exceeding forty years[2], and for the high uncertainty that affects long-term simulations both for climate (greenhouse gas emissions, economic and technological development, renewable energy sources, etc.) and economic reasons (inflation, risks, instability of market prices, etc.).

The difference between the stumpage potential values to 2050 obtained without considering possible climate impacts (SV_{2050}) and the values obtained by separating the vulnerability levels (SV_v_{2050}), financially discounted to 2012, has yielded the estimated economic damage. Moreover, it was decided to refer to Programme Areas[3] and forest types to get more detailed information about the possible economic damages.

4. Results

4.1. Levels of vulnerability, resilience and uncertainty to 2050

The Dempster-Shafer theory does not require complete spatialized data of an event, since it allows two distinct values to express both the Belief of a given assumption and the Belief of an opposite assumption, such as: assumption A1 = localising vulnerability and assumption A2 = localising resilience. The "non-singular" (A1, A2) assumption represents the localisation of both vulnerability and resilience. The assessment of assumptions is based on three key concepts: Basic Probability Assignment (BPA), Belief and Plausibility.

The BPA is the contribution supplied by a given factor (a_i) to support a given assumption (such as the resilience of forests). The estimate of this probability is built on AHP.

Using AHP, the weights assigned to each criterion applied in the analysis were globally assessed. Table 5 shows the results of AHP for the two lines of evidence.

Once the weights of criteria were obtained, the maps of BPA were calculated according to Eq. (1) and then aggregated using the DS theory for the two different lines of evidence, making it possible to calculate the values of the degree of vulnerability and resilience. The DS model also provides a map showing the uncertainty associated with the analysis, due to the simultaneous presence (on the same *pixel*) of high values (or low values) of both vulnerability and resilience.

The vulnerability, resilience and uncertainty levels for the year 2050 were calculated for the whole forest sector of Basilicata, as proposed in Fig. 2.

The results show a vulnerability level with an average value of 0.116 in 2050, with minimum and maximum values of 0.005 and 0.522 respectively, despite the presence of areas where vulnerability levels exceed 0.5. These areas are mostly concentrated in the north-eastern and south-eastern areas of the region, due to the increasing aridity levels. As a matter of fact, the analysis carried out through the calculation of the De Martonne index (De Martonne, 1926), points out the onset of a semiarid climate to 2050 and the achievement of threshold survival conditions for plants in some areas of the region (Fig. 3).

In line with other studies (Bernetti et al, 2010, 2011; de Dios et al., 2007; Matteucci et al. 2011; Pignatti, 2011), with an increase in drought conditions, the most vulnerable forest stands are the Mediterranean pines (in particular the planted stands located on the east coast) and the chestnuts, followed by wood plantations and hygrophilous forests (Fig. 4).

A study carried out in Spanish territory has shown that Mediterranean pine tend to deteriorate very rapidly in places where water stress is intense, even when climate change is only a weak trend (Allue ´-Andrade, 1995). Moreover, since the level of biodiversity greatly influences the adaptive capacity of forests to disturbances, planted stands are in general more vulnerable to climate change with respect to the natural ones (Thompson et al., 2009). As for the chestnuts, historically widespread for economic reasons, they were planted in not optimal conditions (hills and low mountains) and therefore, they have a limited adaptive capacity to heating and drought (Matteucci et al., 2011).

Nevertheless, Basilicata forests show a resilience degree higher than the vulnerability one, with an average value in 2050 of 0.347, within a range of 0.018 and 0.887. The central areas of the region, mostly exposed in the north-west, show the highest resilience values in 2050, basically due to management measures. In fact, forest management plans have deeply influenced, throughout the years, the vulnerability levels to the benefit of forest resilience capacity.

However, the level of uncertainty, assessed on the basis of DS theory, is very high in many areas, showing an average value of 0.514 and peaks between 0.106 and 0.971. The high values observed for uncertainty are attributed to areas that show at the same time low values of resilience and vulnerability. In particular, the high level of uncertainty is recorded in heavily anthropized beech and oak stands, managed mainly as coppice and sometimes without an appropriate forest management plan.

The management systems can have a significant impact on the ability of forests to adapt to climate change (Bottalico et al., 2016; Collalti et al., 2018; Klein et al., 2013). The vulnerability and resilience levels in 2050 in relation to the management systems are shown in Figs. 5 and 6.

The results of the DS model show indeed how the man-made system of forest management have influenced over time the levels of vulnerability and resilience to climate change. Forest ecosystems actually react differently, depending on the varying degrees of human interactions.

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[1] A 3.322%, discount rate has been applied in this research, based on the values provided by the *Cassa Depositi e Prestiti* (Savings and Loans Bank).

[2] Most economic analyses do not exceed thirty-year time intervals.

[3] Art. 23 of the R.L. No 33/2010

Table 5
Assessment of the Belief of vulnerability and resilience via AHP.

Lines of evidence	Variables	Evaluation of belief
Resilience	Management system	0.5128
	Accessibility	0.2615
	Protected areas	0.1290
	Index of variety	0.0634
	Managed forests	0.0333
Vulnerability	Aridity	0.3209
	Vigour	0.3209
	Change in phytoclimatic zone	0.2616
	Slope	0.0634
	Aspect	0.0333

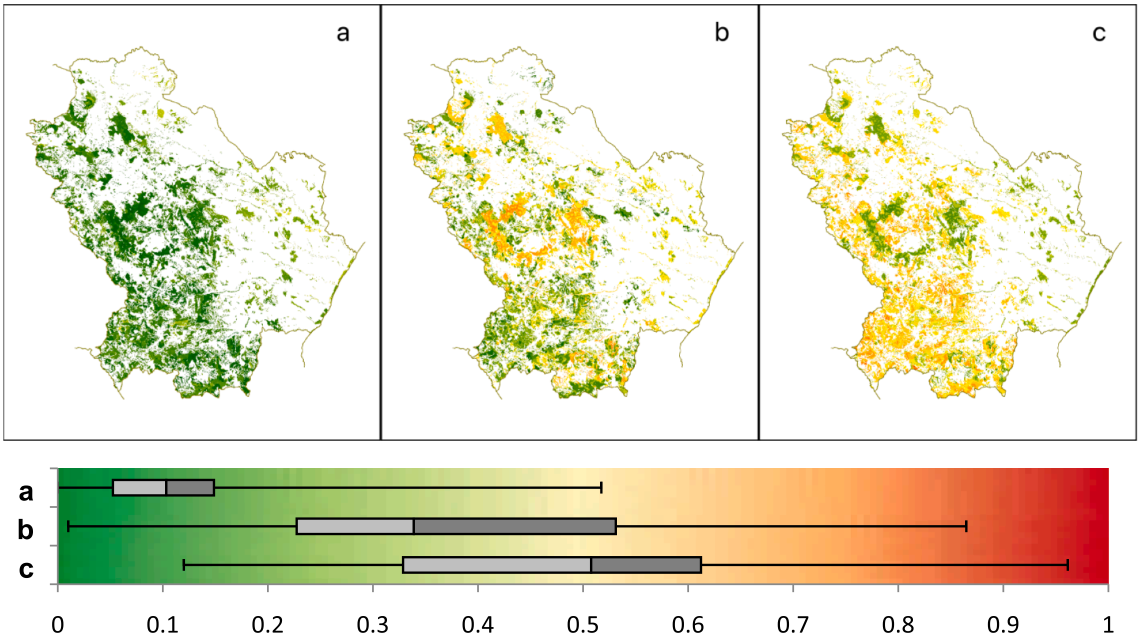

Fig. 2. Regional maps and Box-Plot of vulnerability (a), resilience (b) and uncertainty (c) (year 2050).

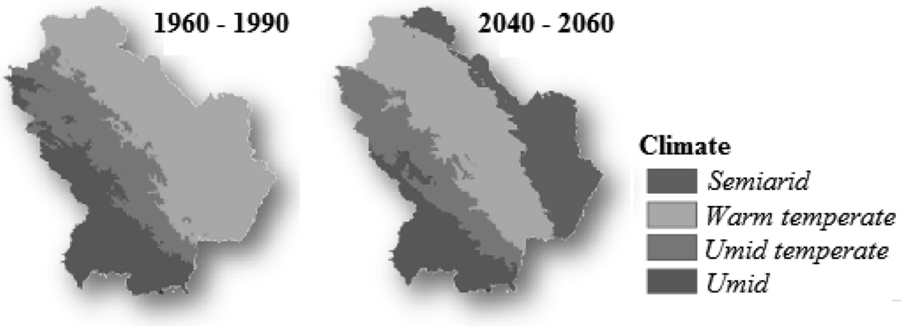

Fig. 3. Maps showing the De Martonne index.

For vulnerability levels in 2050, high forests are in contrast with reforested areas with average values of 0.09 and 0.21 respectively, whereas coppices are in an intermediate position between the two, with an average value of 0.14. The low vulnerability levels observed for high forests are ascribable to the fact that applied measures are similar to the criteria of natural silviculture. On the contrary, reforested areas represent the stands with the highest levels of vulnerability due to their artificial feature.

As for resilience levels, high forests show the highest values followed by reforested areas and coppices. The inversion of values recorded for coppices and reforested areas is justified by the fact that most reforested areas are localised within protected zones (Parks, SCI and SPZ), contrary to coppices that are sited in areas either marginal and/or subject to high human pressure (pasture, clear-cutting with standards, etc.).

Our results are in line with the study of Bottalico et al. (2016) carried out in a Mediterranean area, that show the importance in high forest management to preserve forest ecosystem services (e.g. wood production, carbon storage) and to increase the adaptive capacity of forests to climate change.

4.2. Economic damage assessment to 2050

The economic assessment of the damages caused by climate change to forest systems was based on the potential stumpage prices discounted to 2012, considering the effects of climate change. Table 6 shows the results for different programme areas and for each forest type.

Results show that damages will be minimum for the forest types included in protected natural areas or managed by specific plans. More specifically, in accordance with what is reported by Robert (2008) and more recently by Bernetti et al. (2010) in Tuscany, the major damages (in terms of damaged forest area) attributable to climate change will affect the forests of mountain areas, such as beech forests. In general, the major damage will involve hygrophilous woods with an average damage discounted to 2012 equal to 1.342 €/ha, followed by beech

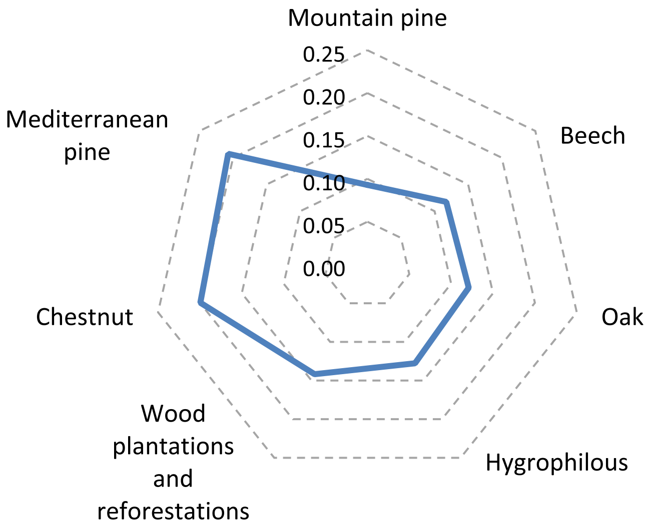

Fig. 4. Mean vulnerability level by forest type in Basilicata region (years 2050).

high forests with 1.183 €/ha and oak coppices with 573 €/ha. The remaining forests show an estimated average damage of €175 per hectare.

In geographical terms, the area most economically exposed to the effects of climate change falls within the administrative boundaries of Matera municipality with an average damage of 1.086 €/ha, followed by the Vulture Alto Bradano Programme Area with a damage of 773 €/ha and the Marmo Platano Melandro Programme Area with 661 €/ha.

5. Conclusions

Climate change has a great impact on forests influencing growth and productivity rates and leading to changes in the composition of existing species, and to altitude and latitude shifts with subsequent loss in biodiversity. The ability to predict events, via climate simulation models, and to assess the possible responses of forest systems may be very helpful to identify action strategies and management techniques aimed to improve the adaptive capacity to climate change.

In our study, the prediction of climate change effects on forests has been based on Dempster-Shafer (DS) theory of evidence, adequately spatialized. The use of methodologies associated with the fuzzy approach and DS theory of evidence are effective tools to integrate data, predict phenomena and assess the impacts derived from climate change.

The applied approach enabled us to predict the forest vulnerability as well as the economic quantification of the impacts derived from a decline in productivity and the subsequent potential economic damage, meant as loss in stumpage value. Results have pointed out higher economic damages for hygrophilous forests, beech high forests and oak coppice, whereas at the geographic level the most severe damages are concentrated in the Vulture Alto Bradano and Marmo Platano Melandro Plateaus.

The applied methodological approach has shown that the high degree of spatial and information detail can provide reliable predictions leading to targeted actions for monitoring, mitigating and combating

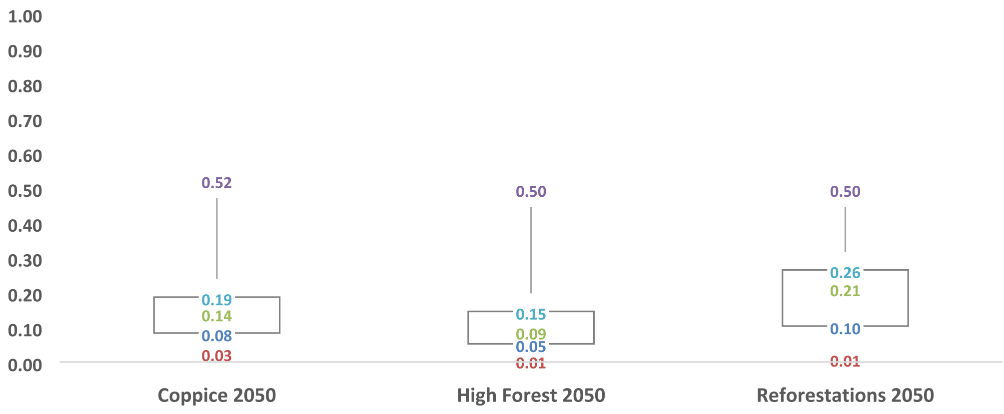

Fig. 5. Box-Plot of vulnerability in 2050 by management systems (coppice, high forests and reforestation).

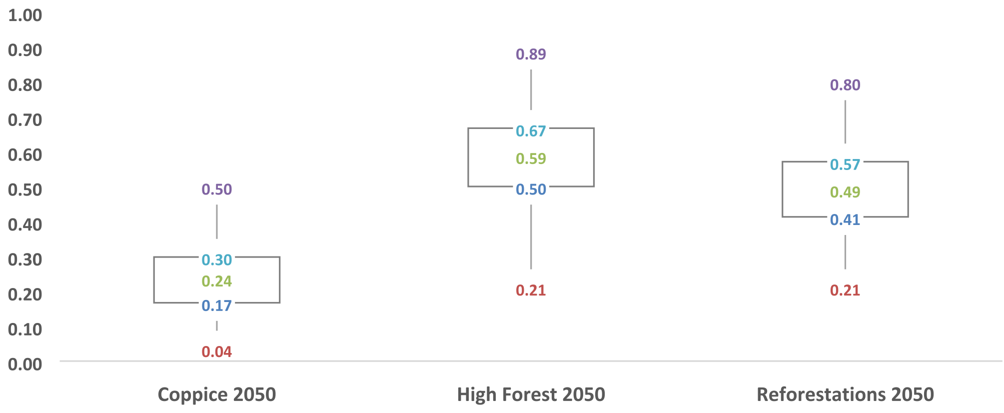

Fig. 6. Box-Plot of resilience in 2050 by management systems (coppice, high forests and reforestation).

Table 6
Economic damages (€ / ha) of forest types grouped by Programme Areas.

Forest type	AP Lagonegrese Pollino	AP Basento Bradano Camastra	AP Val d'Agri	AP Marmo Platano Melandro	AP Vulture Alto Bradano	AP Metaponto Collina Materana	AP Bradano Basento	Potenza	Matera	**Mean damage**
Oak forest (coppice)	378	335	322	433	767	632	768	291	1′227	**573**
Oak forest (high forests)	72	100	103	145	183	157	198	108	–	**133**
Beech forest (coppice)	255	143	327	428	–	–	–	58	–	**242**
Beech forest high forests)	111	787	1′032	3′015	2′134	–	–	16	–	**1′183**
Hygrophilous forest	825	779	627	873	1′563	2′275	2′194	440	2′499	**1′342**
Wood Plantations and Reforestations	101	38	101	118	314	242	331	12	301	**173**
Mediterranean pine forest	101	161	91	121	226	259	312	86,77	318	**199**
Mountain pine forest	112	119	85	151	226	213	20	99	–	**128**
Mean damage	**244**	**308**	**336**	**661**	**773**	**630**	**637**	**146**	**1′086**	

climate change damage. More specifically, for forestry it is necessary that mitigation strategies take into account appropriate adaptive measures, in order to reduce the vulnerability of forest ecosystems to climate change, while adding value to forests in local economies. Among the silvicultural management measures directed to increasing the resilience levels of forest systems, there are forms of treatment that can increase interspecific diversification, augment the existing wood mass, implement measures aimed at converting allochthonous monospecific systems with autochthonous species and, in general, sustainable forest management practices. Mitigation actions shall mostly aim at enhancing the natural adaptive capacity of forests, via the monitoring and implementation of actions directed to increasing the ecological and hydrogeological stability, adopting sustainable cut and hauling techniques, in order to favour the conservation of mineral elements and minimizing soil compaction and humus degradation. These practices need to be complemented by proactive fire prevention actions, structural policies aimed to limit the abandonment of woodland areas, rationalize grazing in highly degraded areas, diversify growth stages and the existing forest types in landscape mosaics, giving the priority to autochthonous species, implement polyspecific forest systems and renaturalise reforested areas.

A special role in these strategies is played by public entities, who are the holders of a considerable portion of the natural and forestry heritage. They are tasked with undertaking forest protection measures, such as the adoption of sustainable forest certification systems, aimed to favour actions to combat climate change and promote the full participation of forest owners to the above strategies, through economic incentives.

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