Chapter 11
Severe Wildfire in a Mediterranean Forest

Roberto Molowny-Horas, Armonía Borrego, Pere Riera and Josep Maria Espelta

Abstract This case study illustrates the equivalency analysis for estimating *ex post* environmental damage and appropriate compensatory remediation following a severe wildfire caused by a power line in a forest protected under the European Union Habitats Directive (HD). The study addresses long-term environmental damage (e.g., over several decades) by a large-scale disturbance in a terrestrial ecosystem, and includes an analysis of uncertainty associated with the potential occurrence of natural future fire events in the area. Accounting for the probability of natural future forest fires directly affects both baseline and compensatory remediation options by reducing the habitat area compared to an assumption of no future forest fires. Only natural forest fires, i.e., 10% of all forest fires, have been included in the calculations of both the baseline and the compensatory remediation, since the operator may not be made liable for accidental or provoked forest fires. The impact of this hypothesis is tested by means of a sensitivity analysis. The case study illustrates:

- Considerations in selecting a metric from various potential ones (hectares, trees, biomass, habitat quality) for terrestrial habitats included in the HD;
- Application of a value equivalency approach (specifically, value-to-value);

R. Molowny-Horas (✉) · J. M. Espelta
CREAF, Cerdanyola del Vallès 08193, Spain
e-mail: roberto@creaf.uab.es

J. M. Espelta
e-mail: josep.espelta@uab.cat

A. Borrego
Center for Research in Environmental Geography, National Autonomous University of Mexico (CIGA—UNAM), Antigua Carretera a Patzcuaro 8701, Morelia, CP, 58190 Michoacan, Mexico
e-mail: aborrego@ciga.unam.mx

P. Riera
Institute of Environmental Sciences and Technology, Autonomous University of Barcelona, ICTA, Edifiici Z, Campus UAB, 08193 Bellatera, Spain
e-mail: prieram@gmail.com

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- Analysis of key variables (e.g., differences in metrics, single/multiple metrics, on-site/off-site implementation); and
- Sensitivity of the results to changes in four key model parameters (i.e. area of future forest fires, tree mortality, percentage of natural forest fires and tree minimum diameter at breast height).

Keywords Habitat equivalency analysis · Value equivalency analysis
Forest wildfire · *Pinus nigra*—simulation model · Spain

11.1 Introduction

This case study illustrates the application of equivalency analysis to the remediation of long-term environmental damage to a terrestrial habitat protected under the Habitats Directive (HD). The so-called *Bages-Berguedà* application (hereafter, BABE) presented here is of interest for two main reasons: first, it shows the application of Habitat Equivalency Analysis (HEA), Resource Equivalency Analysis (REA), and Value Equivalency Analysis (VEA) to the compensation of long-term, large-scale environmental damage that in turn may need large-scale and relatively expensive compensatory measures to be applied. Second, it exemplifies the application of simulation models to deal with the complexity associated with the evaluation of the habitat recovery.

The steps usually followed in applying HEA, REA, and VEA are adapted to suit this particular case study. Section 11.2 describes the incident and the affected habitat and summarises the available data (forest inventories, wildfire datasets, and forest management practices) that will be used in the analysis. Section 11.3 presents the main baseline parameters and the four metrics used in the analysis and discusses the calculation of debit evaluation, including natural, primary recovery, and total interim loss. Section 11.4 describes and assesses the two compensatory remediation options (afforestation of selected areas and fire-prevention plans) that have been selected. In Sect. 11.5, the scaling of the compensatory remediation is calculated, as well as the costs involved, and a sensitivity analysis of key model parameters is presented. Section 11.6 provides a short description of how the recovery of the affected area should be monitored regularly. Finally, Sect. 11.7 summarises the study and discusses the implications of the results.

11.2 Initial Evaluation—the Impact Event

11.2.1 Description of the Incident

Between 4 and 8 July 1994, a large forest fire (Fig. 11.1) occurred in the Catalan counties of Bages and Berguedà, located in northeast Spain (410 45′ to

420 6′ N; 10 38′ to 20 1′ E). The fire was caused by a malfunctioning power line. There are previous cases in the same region and in neighbouring areas where power companies have been declared legally liable for the accidental ignition of wildfires due to poorly maintained power lines (e.g., the Solsonès County wildfire that burned 14,000 ha in 1998). Official reports on forest fires in Mediterranean countries estimate that approximately 17–21% of forest fires are caused by power line malfunctions (Peix i Massip 1999).

The BABE wildfire burned approximately 25,000 ha of European black pine (*Pinus nigra* subsp. *salzmannii*). Black pine forests are included in Annex I of the HD (9530, *Sub-Mediterranean montane forests with endemic black pines*) and they are assigned a high priority for conservation. Sub-Mediterranean black pine forests are present in Italy, Greece, Corsica, and Spain.

The BABE wildfire had an extraordinary impact both in ecological and socioeconomic terms. Black pine is a fire-sensitive species, and natural postfire regeneration is very limited. The new forest landscape that appeared after the fire event included the presence of large areas without any tree regeneration, as well as significant changes in the forest tree species (e.g., mixed oak coppices through resprouting; Retana et al. 2002). Overall the wildfire led to a one-third reduction in the total area of the black pine in Catalonia. The wildfire also impacted popular recreational activities, such as hunting and mushroom-picking, and other tourist-related industries, all of which were drastically reduced after the fire. Black pine does not have any mechanism to survive or to regenerate after intense fire events (Espelta et al. 2003). Therefore, the natural recolonisation of the burned area by black pine is expected to take an extraordinarily long time, or never occur at all, unless proper remediation measures are implemented.

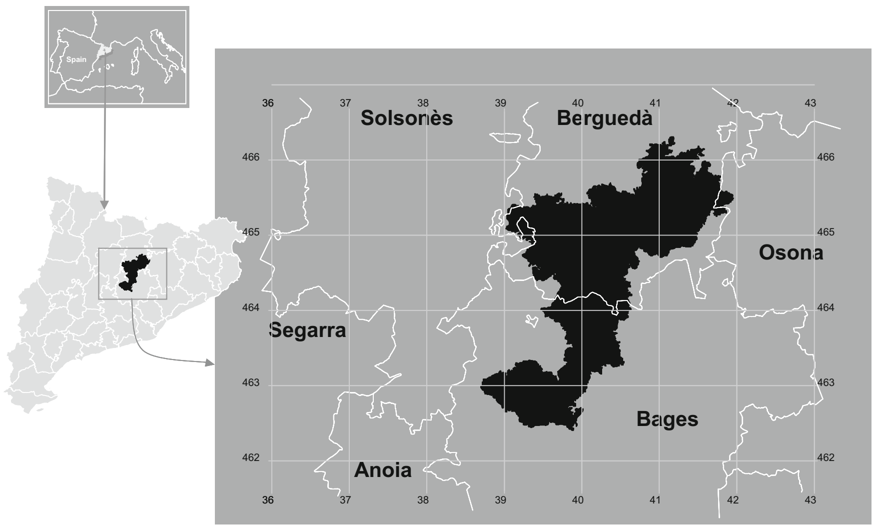

Fig. 11.1 Geographic location of Catalonia and the 1994 BABE fire

11.2.2 Description of the Habitat Affected

The European black pine (*Pino laricio* or *Pino negral* in Spanish; *Pinassa* in Catalan; see Fig. 11.2) is the fourth most abundant tree species in Catalonia in number of stems after *Quercus ilex* (holm oak), *P. sylvestris* (scots pine), and *P. halepensis* (aleppo pine). It is also the fourth most extensively distributed tree species in terms of area (ha) (Burriel et al. 2000–2004). In Catalonia, black pines can be found at elevations ranging from 400 to 1,500 m. Preferring slopes facing north, it can grow up to 40 m or more in height and up to 80 cm or more in diameter at breast height (Bolòs et al. 1993).

Black pine cones open from December to April. Their winged seeds can disperse to nearby areas, even though dispersion distances of up to 100 m or more have been measured in open areas (Ordóñez et al. 2006). If local conditions are appropriate, seeds germinate and establish in the Spring, at the end of which seedlings grow to a few centimeters high.

Black pine lacks any kind of protective or defensive mechanism against fires: its bark is thinner than that of other Mediterranean pine species (like *P. pinaster*); it does not resprout from the stump after a fire (like *Q. ilex*); and it does not have a canopy seed bank (like *P. halepensis*). It is essentially a defenseless species against fires and, as such, it suffers the most during the summer wildfires that regularly affect the Mediterranean forests. Unsurprisingly, its natural regeneration following a severe fire is very low, which together with the high recurrence of forest fires in the Mediterranean basin causes a relentless reduction of its current habitat.

Fig. 11.2 An example of a black pine forest in Catalonia

Black pine forests, referred to as (sub-) Mediterranean pine forests with endemic black pines, are listed in Annex I of the HD and hence can be regarded as a European protected habitat in terms of the Environmental Liability Directive (ELD). The Interpretation Manual of European Union Habitats (European Commission 2007) specifically refers to *Pinus nigra* subspecies *Salzmanni*. The distribution of Salzmann's pine forest is described as follows: *Pinus salzmannii* forests of Spain (Pyrenees, northern Iberian Range, sierra de Gredos, serranía de Cuenca, Maestrazgo, sierras de Cazorla, Segura and Alcaraz, calcareous periphery of the Sierra Nevada) and the Caucasus.

11.2.3 Available Data

There are three main data sources that were used in this analysis which are described in this Section: forest inventory, forest fires, and silviculture practices.

11.2.3.1 Forest Inventory Data

The Spanish 2nd and 3rd Inventarios Forestales Nacionales (National Forest Inventories) were finished in 1990 and 2000–2001 and represent the main datasets with which to carry out the present analysis. Moreover, in 1994, a similar, more ecologically focused endeavor, the Inventari Ecològic i Forestal de Catalunya, i.e., Ecological and Forest Inventory of Catalonia (see Gracia et al. 2002), was completed by several teams from Center for Ecological Research and Forestry Applications (CREAF). Allometric equations relating diameter at breast height and tree height, tree growth, and biomass weight, were computed from this dataset.

In the short time interval from 1990 to 1994 (before the fire), the BABE forest was not affected by events of any type (e.g., fires, road construction) that could have significantly altered its structure or composition. It has been assumed that the 1994 pre-fire BABE forest is basically indistinguishable from the 1990 BABE forest described in the 2nd Spanish inventory. The latter can then be used to describe the structure of the 1994 pre-fire black pine stands.

11.2.3.2 Forest Fire Data

One can reasonably assume that the size and frequency pattern of forest fires in future years will match those of past years. Moreover, as stated in Article 4, Section 1b, of the ELD, the Directive '*shall not cover environmental damage or an imminent threat of such damage caused by a natural phenomenon of exceptional, inevitable and irresistible character*.' It is well known that in Mediterranean-type ecosystems, fires are a common disturbance and may be considered to be part of their natural dynamics (Terradas 1996). If one distinguishes between natural and human-caused forest fires, it must be concluded that operators should be made liable for damages caused by human-induced fires but not by those of natural origin. Previous studies carried out between 1996 and 2005 have shown that in Catalonia, only about 10% of all forest fires are due to a natural cause (i.e., lightning), whereas about 11% are due unknown causes. All other fires are accidental or deliberate (Dirección General de Biodiversidad 2007). Therefore, only natural forest fires were included both in the baseline and in the compensatory remediation calculations.

11.2.3.3 Silvicultural Practices

Traditional management practices consist of selective thinning and pruning. Usually only larger trees are thinned. As a simplification, one can assume that low or moderate cutting does not modify forest density enough as to decrease fire risk. A straightforward, yet realistic, selective thinning approach was implemented whereby trees with a diameter at breast height larger than 30 cm are cut, but only in those stands where basal area is larger than 20 m^2/ha (see Table 11.1).

11.3 Determining the Debits

11.3.1 Baseline Parameters

The temporal evolution of the different metrics was calculated with the aid of appropriate mathematical forest models. Those simulation models assumed that:

- The initial forest was mono-specific and would remain so during the calculations, and
- The forest was almost fully stocked.

These two assumptions considerably simplify the construction of the algorithms and speed up the calculations. As a result of the first hypothesis, the original mono-specific forest does not change its composition in time and no other species need to be introduced in the simulation. The second hypothesis implies that self-thinning, that is, the tendency of less-successful trees dying off as the

Table 11.1 BABE Forest Fire—Forest management practices used in the habitat and resource equivalency analyses

Minimum diameter at breast height to cut (cm)	30
Minimum stand basal area (m^2/ha)	20
Frequency	Annual

Table 11.2 BABE Forest Fire—Variables in the equivalency analysis

Start year	1994
End year	2093
Spatial extent of damage (ha)	25,000
Base year	2007
Annual discount rate (%)	3
Degree of service loss (%)	100
Baseline shape	Dynamic
Recovery rate	Metric-dependent
% of forest fires to affect the BABE area	10

most-successful ones grow bigger, becomes an important factor early in the temporal evolution of the forest.

Table 11.2 provides a summary of the parameters used in HEA/REA calculations. The base year of 2007 was used to calculate all compensatory measures. Consequently, those measures will have to be compounded between 1994 and 2007 and discounted afterward. The BABE area was assumed to have been affected only by 10% of all possible fires, i.e., those of known natural origin.

As described in the 2nd National Forest Inventory, before the fire, there were approximately 25,000 ha of black pine forest in the BABE area, containing approximately 18,150,000 black pine trees. Table 11.3 shows the main structural characteristics of the pre-fire BABE forest.

11.3.2 Metrics

In choosing a measure of loss and gain, or 'metric,' one wants to evaluate the impact of, and recovery from, a given environmental damage in a terrestrial ecosystem. In general, the inner workings of most ecosystems are extremely complex, and their properties and rules are sometimes poorly understood. Ecosystems also interact with their surroundings, which complicates things further. Regarding the BABE forest, one can choose a set of appropriate metrics in order to determine the success of the forest's recovery from the 1994 wildfire. The degree of loss or recovery following implementation of the remediation plans outlined below was determined by calculating the following non-monetary metrics, which are measured per hectare and then summed for the whole BABE area:

Table 11.3 BABE Forest Fire—Structural parameters of the pre-fire BABE forest

Area covered by black pine trees (ha)	25,000
Total number of trees	18,150,000
Tree density (trees/ha)	726
Mean height (m)	8.2
Mean diameter at breast height (cm)	13.6
Mean basal area (m^2/ha)	12.5

- *Total number of trees with diameter at breast height larger than 7.5* cm: A convention was used, as applied in forest inventories elsewhere, such that only trees with Diameter at Breast Height (DBH) (1.3 m) larger than 7.5 cm are counted. The impact of this choice on the final results was tested by means of a sensitivity analysis;
- *Total area covered by trees*: The criteria of minimum canopy cover (>50%) per hectare was used as a threshold to determine whether or not tree cover is high enough to count as a full forest. This assessed the area occupied by the habitat;
- *Total biomass*: Biomass (wood) is directly related to the carbon dioxide (CO_2) captured by the forest, i.e., there is approximately 0.5 kg of carbon in 1 kg of black pine wood, and
- *Total habitat quality index*: A normalised index that took into account the existence of large trees (measured by their DBH and their height) and the total basal area occupied per hectare.

In addition, a welfare or monetary metric is considered to estimate debits and scale remediation using a value-to-value approach. It is measured in monetary terms for the whole affected area, rather than on a per hectare basis, reflecting the welfare loss associated in the interim due to the forest fire and until full restoration back to baseline.

11.3.3 Debits

11.3.3.1 Baseline Determination

A numerical forest model was used in order to assess the complex future evolution of the baseline forest (see Appendix A). The algorithm took into account the non-zero probability of suffering forest fires of natural origin in the future. Fires were subsequently incorporated into the model as a simplified and easy-to-implement stochastic fire submodel (Appendix B), where their annual distributions of size and frequencies were given by the empirical datasets described above. The output of the forest model consisted of the four non-monetary metrics described above and the extent of the burned area per year.

Figures 11.3a, b, c and d[1] show the evolution of the four metrics from 1994 to 2094. To further illustrate the impact of fires, the evolution of the corresponding average metrics with no future fires was also plotted. The plots follow different paths depending on the impact of fires randomly distributed in time and space. Fires cause metric values to differ as compared to a scenario without future fires, and the

[1]The 100-year simulation has been repeated 100 times. Mean 5 and 95% percentile bars are shown in the plots in gray. The baseline without future fires has been plotted in black. The forested area metric remains at a constant value of 25,000 ha because no future fires are included in the calculations.

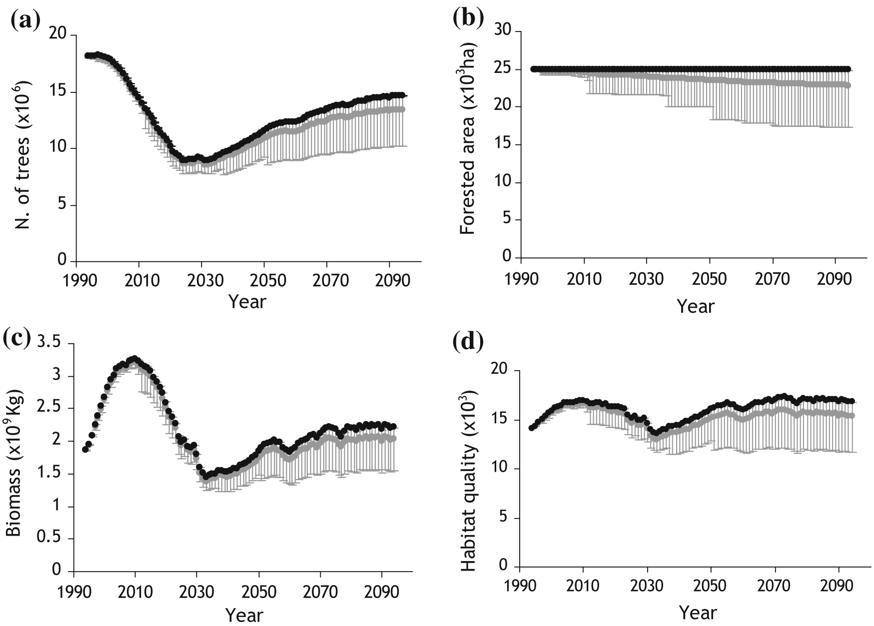

Fig. 11.3 **a** Total number of trees metric, baseline from 1994 to 2094. **b** Total forested area metric, baseline from 1994 to 2094. **c** Total biomass per hectare metric, baseline from 1994 to 2094. **d** Total habitat quality metric, baseline from 1994 to 2094. Metric values without forest fires are plotted in black

different possible trajectories followed by the baseline can be seen as large percentile bars around the mean. Self-thinning also causes the number of trees in the almost fully stocked forest to steadily drop from a starting value of about 18 million to about 8 million and then to slowly increase up to a constant value of about 13 million, which is reached after approximately 150 years (not shown here). The percentile bars are also different in both cases, being undetectable (at the scale of the figure) in the case of no future fires. The impact of future fires is thus twofold: first, they decrease the total number of trees and, second, they introduce a larger scatter in the metric, which stems from the different possible trajectories followed by the simulations. Notice that when future fires are discarded, the value of the forested-area metric remains constant in time, as expected.

11.3.3.2 Natural Recovery

To evaluate the likelihood of the BABE burned area returning by itself to pre-fire conditions, a spatially explicit simulation model of the recruitment of black pine trees from unburned edges was applied (see Molowny-Horas et al. 2007) for a thorough explanation of that model). Seeds from trees along the border of the unburned edge of the forest are dispersed by wind into the burned forest. Some of those seeds may survive, germinate, and then establish and grow. The rate at which this process takes place will determine the speed by which the burned area will naturally recover from the fire.

The evolution of the four metrics as a function of time (not shown here) at several distance intervals from the unburned edge, as simulated with this model, confirmed that the speed of recovery is painfully slow and clearly does not guarantee the recovery of the BABE area within any reasonable time interval. These results were validated by field work carried out in the area (Rodrigo et al. 2004). Moreover, other tree species better adapted to post-fire conditions would soon begin competing with black pine seedlings for light, soil nutrients, and water, further hindering the successful establishment of any black pine trees. It is assumed hereafter that natural recovery is negligible, and consequently primary remediation will be required. For these reasons, only the simulation model of Appendix A is used in the following descriptions.

11.3.3.3 Primary Remediation in the BABE Area: Black Pine Reforestation

As discussed above, the burned BABE area will not return to pre-fire conditions unless steps are taken to remediate the damage. No actions were taken after the fire in 1994 that could count as primary remediation. It is assumed here that to compensate for the habitat loss, the primary remediation strategy to be carried out right after the fire consisted of extensive black pine reforesting in the burned area. Given the extent of the area burned in 1994, tree planting may in practice require several years in order to cover the whole area, depending on budgetary and practical constraints. Moreover, the optimum season to plant black pine seedlings is from February to March, which limits the number of days to plant. As will be explained later, these primary remediation measures could instead be considered as part of the compensatory remediation actions to take place after the fire.

Figures 11.4a, b, c and d[2] show how the proposed primary remediation would return the BABE forest to the baseline. Drawing from the experience of previous reforestation plans in Catalonia, a planting rate of 2,500 ha per year was chosen. Initial density of planted seedlings was 1,500 stems/ha (Espelta et al. 2003). The number of seedlings may have to be increased if initial seedling mortality linked to the early post-transplant period is unacceptably high. The reforestation was assumed to stop after 10 years, when the initial 25,000 ha are replanted (see Table 11.4). However, a percentage of those 25,000 ha was assumed to be lost to new fires. It was also assumed that fires can affect both young plantations and mature trees alike and no effort was made to compensate these losses to 25,000 ha reforested after the initial 10 years.

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[2]The corresponding baseline metrics from the previous figure are included for reference in black. 5 and 95% percentile bars are plotted around mean values.

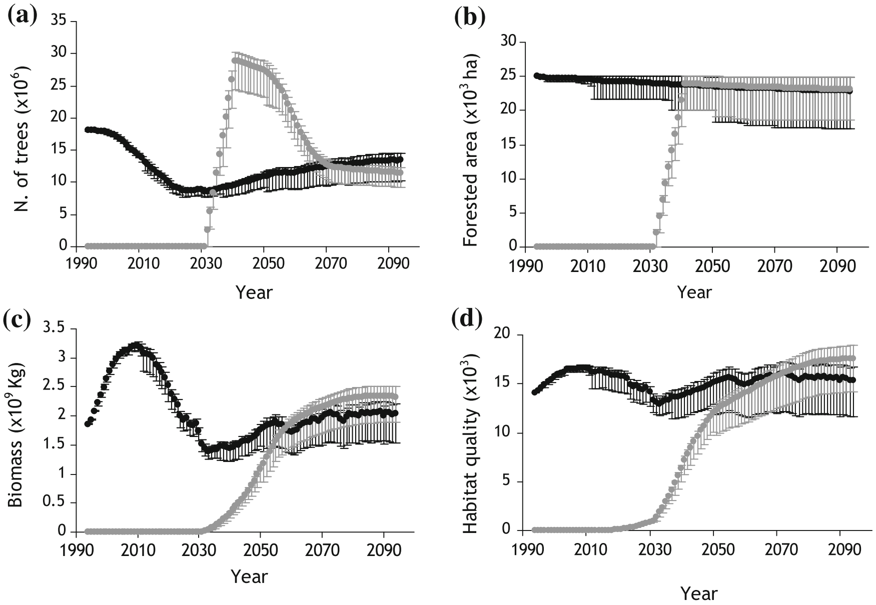

Fig. 11.4 **a** Total number of trees metric, primary remediation (in grey) from 1994 to 2004. **b** Total forested area metric, primary remediation (in grey) from 1994 to 2094. **c** Total biomass per hectare metric, primary remediation (in grey) from 1994 to 2094. **d** Total habitat quality metric, primary remediation (in grey) from 1994 to 2094. Baseline metric values are plotted in black

Table 11.4 BABE Forest Fire Parameters for primary remediation: Black pine reforestation

Start year	1995
End year	2004
Total reforested area (ha)	25,000
Reforested area per year (ha)	2,500
Number of planted seedlings (ha)	1,500

As noted, a 'tree' was defined as a stem with a DBH larger than 7.5 cm. Note that the four metrics in Fig. 11.4 become measurably larger than zero only at the time when the diameters of the earliest plantations become larger than 7.5 cm, which is approximately in 2030, 36 years after the fire. Notice the different behaviours of the four metrics. Although the total reforested area reaches baseline values relatively early (2040), the number of trees very quickly exceeds baseline values (2034) and then slowly converges down to the baseline in the long term. Biomass and total habitat quality, on the other hand, reach values slightly higher than those of the baseline.

11.3.3.4 Determination of Interim Loss

The interim loss to compensate for is defined by the area between the baseline and the primary remediation curves shown in Fig. 11.4. Table 11.5 reflects the

Table 11.5 BABE Forest Fire—Nominal and discounted interim loss calculations

Year	Nominal number of trees loss ($\times 10^6$)	Nominal habitat area loss ($\times 10^3$ ha)	Nominal biomass loss ($\times 10^8$ kg)	Nominal habitat quality loss ($\times 10^3$)	Discount factor (at 3%)	Discounted number of trees loss ($\times 10^6$)	Discounted habitat area loss ($\times 10^3$ ha)	Discounted biomass loss ($\times 10^8$ kg)	Discounted habitat quality loss ($\times 10^3$)
1994	18.14	25.0	18.60	14.10	1.47	26.64	36.71	27.31	20.70
1995	18.06	24.91	19.35	14.30	1.43	25.74	35.52	27.59	20.38
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
2033	3.15	19.45	13.45	11.09	0.46	1.46	9.02	6.23	5.1
2034	0.34	17.03	13.39	10.76	0.45	0.15	7.67	6.03	4.8
⋮		⋮	⋮	⋮	⋮		⋮	⋮	⋮
2039		4.79	11.87	8.10	0.39		1.86	4.61	3.15
2040		2.30	11.23	7.39	0.38		0.87	4.23	2.79
⋮			⋮	⋮				⋮	⋮
2056			11.87	2.10	0.23			0.49	1.72
2057			11.23	1.36	0.23			0.31	1.45
⋮				⋮	⋮				⋮
2070				0.06	0.16				0.01
2071				0.04	0.15				0.01
Total						491.37	882.31	966.37	587.93

Note To shorten the table, some of the results were omitted and substituted by the ellipsis. Years for which interim loss becomes negative (and, therefore, will be included as a credit in the calculations) are also omitted calculation of the interim loss as a function of time for the four metrics. The same table also shows the annually discounted interim loss, with a 3% discount rate. Notice that since the base year for discounting is 2007, values from earlier years are compounded.

The evaluation of interim loss, as shown in Table 11.5, ends when interim loss reaches zero. Nevertheless, compensation from primary remediation may exceed total damage to the BABE area if the number-of-trees metric is used. This is clearly seen in Fig. 11.4, where primary remediation for that metric matches or even exceeds the corresponding baseline. This means there is no need for complementary remediation. Total resource loss will then be overcompensated. That overcompensation will be included in the following calculations as a credit when determining the need for compensatory remediation to offset interim losses. Notice that this would generally not be the case if instead of the number of trees, the metric chosen was the number of equivalent mature trees, for which biomass could be taken as a proxy.

11.3.3.5 Interim Loss in Welfare Terms

The debit estimation in monetary terms was undertaken by a contingent valuation (CV) exercise. The CV method attempts to directly measure the public's welfare loss (debit) by administering a specially designed questionnaire to a sample of the affected human population. The questionnaire for the BABE case study followed the customary approach in natural resource damage assessment: it asked for respondents' willingness to pay (WTP) for a program that would avoid a similar loss to the one that occurred (Adamowicz et al. 1998; Bishop et al. 2000). The loss was defined as the forest damage due to fires measured in terms of hectares of black pine forest (the same metric used in the ecological assessment). While any of the other metrics could also have been used, to have same/similar metrics across different assessment is useful for this case study. The time span of the interim loss until full recovery of the forest was said to be 50 years.

The questionnaire was designed through a series of focus groups and a pilot test during the last quarter of 2007. The full survey took place in the first quarter of 2008. The estimates obtained are considered to be 2008 values. In the main survey fieldwork, a total of 400 individuals were interviewed in person.

The sample was selected within the province of Barcelona, where the fires being assessed occurred. A total of 5.3 million people live in the Barcelona province, of which nearly 4 million are at least 18 years of age. The sample was selected using a mixed approach. The municipalities and the locations within the municipalities were randomly selected according to their population weight. The individuals interviewed within each location followed a gender and age quota representative of the overall population of 18 years of age or older. A typical interview lasted approximately 14 min. No significant problems were detected in the interviewing process.

The willingness to pay question took the form of a 'single bounded dichotomous choice', where respondents were asked whether they would be willing to pay € x for the proposed program that would avoid the described forest loss. The amount varied in 10 subsamples as: €10, €20, €40, €50, €60, €70, €80, €100, €120, and €150. The payments were to be made every year for 10 years, and they would go up every year according to inflation.

A standard statistical procedure (see, e.g., Hanemann and Kanninen 1999) was used to estimate the WTP distribution, resulting in just under €60 per individual per year to be paid over 10 years. This corresponds to real values of 2008 Euros, since respondents were told that the payment would be revised according to consumer price inflation. A real discount rate could be applied to obtain the discounted values.

11.4 Determining the Credits

11.4.1 Remediation Alternatives

Following primary remediation (tree planting) conducted on site, the BABE forest would be restored to full baseline conditions. This eliminates the need for complementary remediation. However, full recovery will only be achieved after a long time, which brings about the need to introduce compensatory remediation to compensate for the interim losses. The case study evaluated two alternatives:

- An off-site compensatory remediation plan consisting of the afforestation of available areas in Catalonia with black pine trees, and
- A large-scale fire-prevention plan involving splitting large forests up into smaller forested areas separated by firebreaks.

11.4.2 Calculating Credits

11.4.2.1 Off-Site Afforestation

Geographic Information System (GIS) techniques were used to determine the areas in Catalonia (other than BABE burned area) appropriate for planting black pine seedlings. The following set of digital maps were used:

- Map of the potential distribution of black pine in Catalonia (Thuiller et al. 2003), created from forest databases containing climatic and topographic data, in order to determine the areas where black pine trees can grow. These are potential areas in the sense that if seedlings were planted there, they would be able to establish and grow;

- Map of the local slope, calculated with Miramon GIS (Pons 2007) from a 15 × 15 m per pixel digital elevation map elaborated by the Institut Cartogràfic de Catalunya (ICC);
- Land cover map of Catalonia, available from the Generalitat de Catalunya website, and
- Forest fire map of Catalonia from 1975 to 1994 (Díaz-Delgado and Pons 2001).

The areas that meet the following criteria are deemed to be 'appropriate':

- They must correspond to areas not affected by fires at least since 1975, which is the first year for which detailed statistics and digital maps of the extension of fires exist;
- The topography must be such that it is easily accessible by both vehicles and technicians on foot. Following standard practices in Spanish silviculture, an upper limit of 50% was set to the local slope.
- Successful tree planting must only take place where there is relatively little vegetation and where the presence of other tree species is negligible so that large-scale clear-cutting and soil preparation can be avoided. Areas of shrubs, bushes, and abandoned grasslands (which require minimum preparation, e.g., ripping) were selected as potentially appropriate for planting according to digital land cover maps from the Generalitat de Catalunya.
- They must lie within the perimeter of the potential distribution map of Catalonia from 1975 to 1994 (Thuiller et al. 2003).

The Miramon GIS (Pons 2007) spatial analysis tools were used to determine those areas that fulfill the four conditions above. The resulting digital map (Fig. 11.5) illustrates where the compensatory remediation could take place. The map shows a fractioned landscape of small stands scattered mainly over central and north Catalonia, although some appropriate zones do also exist further south. In all, the analysis found 128,000 ha that could be considered to be the most advantageous for the seedling planting scheme to succeed.

Small isolated forest patches will arguably have a lower ecological value than adjacent areas that can eventually merge to create a larger area. The latter effect would reduce fragmentation and in turn increase the ecological value of the forest. To evaluate the amount of fragmentation introduced by the new potential areas determined above, the nearness to existing patches of forest (of any tree species) was taken into account. The results of a GIS analysis of the whole Catalan territory show that the final, i.e., after afforestation, number of forest patches with area smaller than 100 ha (which was chosen as a threshold) will actually decrease, albeit marginally, when the new potential areas are included. That is, afforestation of the scattered areas slightly reduces the fragmentation of the Catalonian forests.

Planted areas can also be affected by fires. The likelihood of such fires was included in the simulation analysis in the same way it was for the primary remediation plan outlined above. Figure 11.4 includes a graphical description of the evolution of the metrics when 25,000 ha are afforested at a rate of 1,500 ha per year.

Fig. 11.5 Spatial distribution of optimal zones (gray-shaded areas) for planting black pine seeds. *Note* The continuous gray-shaded area corresponds to the BABE forest, as in Fig. 11.1. The city of Barcelona is located in the 'Barcelonès' county, south-east from the BABE area

The discounted and accrued unit credit per hectare for each of the four non-monetary metrics was calculated for the time period 1994–2093. Results are shown in Table 11.6. These calculations included, as a credit, the overcompensation that stemmed from the implementation of the primary remediation (see above).

This compensatory remediation option was presented in the contingent valuation questionnaire mentioned above. The location of the afforestation area varied across subsamples following the geographical pattern reflected in Fig. 11.5. The size of the afforestation area also varied from 10 to 100% of the BABE damaged surface. Figure 11.6 shows an example of the cards included in the contingent valuation questionnaire.

Table 11.6 BABE Forest Fire—Accrued and discounted unit credit per hectare for the four metrics

Metric	Total unit credit
Number of trees	10,420.6
Forested area (ha)	11.16
Biomass (10^3 kg)	644.26
Total habitat quality index	6.01

Fig. 11.6 Example of location and size of burned area and afforestation area. *Note* The percentage of the BABE burn area (for afforestation), shown in the light-shaded area, used in the credit estimation of the value-to-value exercise. The approximate location and size of the BABE burn area are shown in black

11.4.2.2 Fire Prevention

A fire-prevention plan was implemented in which a forest area was divided into smaller patches separated by firebreaks. These isolated patches prevent a fire that started somewhere within one area from spreading and affecting the whole forest. Instead, the combination of firebreaks and more conventional fire-extinguishing strategies (not evaluated here) limit the size of any possible wildfire.

Instead of simply cutting and clearing swaths of forest to make room for the firebreaks, existing crop fields and other non-forested areas may be used to distribute the different forest patches. This fire-prevention plan involves active management of agricultural land adjacent to forest land. Local authorities or government agencies are assumed to financially support land owners to help them shift crops. These crops should be chosen such that their phenological cycle coincides with the hot season so that they stay green throughout the summer until the fall harvest. Greener crops are much more difficult to burn than dry crops such as postharvest corn and will therefore present a more effective barrier against the propagation of a fire. If managed correctly, these new protective buffer areas will stop fires from progressing from one area to the next. The feasibility of implementing this compensatory measure to the Catalonian forests is not discussed in this analysis, although a similar study for an area adjacent to the BABE forest can be found in Ibáñez et al. (2007). The remediation strategy proposed here is based on the work by those authors.

This particular compensatory remediation strategy can actually be thought of as:

- On-site or off-site *ex ante* (plans can be set up in fire-prone areas to prevent damage on-site or compensate for future fires off-site) or
- Off-site *ex post* (once the fire has occurred, a prevention plan can be set up to compensate for future fires in off-site areas).

In both cases, it is necessary to evaluate the amount of forest that will be prevented from burning every year.

A detailed and exhaustive application of this compensatory strategy to a specific case was beyond the scope of this case study. Instead, a more simplified analysis was undertaken in which an imaginary 5,000-ha forested area was enclosed by a firebreak. The wildfire sub-model described above was then applied to this area to calculate the average amount of forest that was burned per year. Obviously, no single fire could be larger than 5,000 ha in this case. For the sake of illustration, Table 11.7 shows the comparison of average annually burned area between the 5,000-ha forest just described and an unprotected 25,000-ha forest. Scaling the 5,000 ha results up to 25,000 ha yields 160 ha. The difference between averages then gives 46 ha (= 206 − 160) per year.

Table 11.8 also shows the unit credit (discounted and accrued) corresponding to this compensatory remediation strategy for the four metrics of the study. Clearly, the impact of the fire-prevention plan is very small, which becomes apparent when scaling of this compensatory plan is performed (see below).

Table 11.7 BABE Forest Fire—Calculation of average annually burned area for the fire prevention remediation plan

Total area (ha)	Average area burned per year per hectare
5,000 (25,000) Fire prevention plan	32 (160)
25,000 unprotected	206
Difference for 25,000	46

Table 11.8 BABE Forest Fire—Unit credit calculation per hectare for the fire prevention compensatory remediation plan

Metric	Unit credit
Number of trees	61.6
Forested area	0.088
Biomass (10^3 kg)	6.3
Habitat quality index	0.05

11.5 Scaling Remediation

11.5.1 Scaling off-Site Afforestation

The size of the required compensatory remediation in an off-site area from 1994 to 2093 was assessed. Planting rates were similar to those adopted in the primary remediation (see above) and were scaled as needed. Table 11.9 shows the results of scaling off-site afforestation to compensate the interim loss.

The size of the compensatory remediation measure is smaller when the number-of-trees metric is selected, followed by the forested-area metric. Biomass and habitat-quality metrics, on the other hand, which are arguably more related to the actual ecological value of the ecosystem, require much larger compensatory remediation. Table 11.9 clearly indicates that scaling can give different results depending on the metric that is used. It also demonstrates that assessing the ecological implications of the impact of the BABE forest fire requires, as shown here, careful evaluation of several options to carry out an adequate compensation.

As mentioned, a valuation exercise was implemented to estimate the debit or interim loss in monetary units (Sect. 11.3.3). A second contingent valuation exercise was performed to estimate the scale of the compensatory remediation (the

Table 11.9 BABE Forest Fire—Scaling the off-site afforestation remediation plan

Metrics	Size of compensatory remediation (ha)
Number of trees	36,133
Forested area	70,442
Biomass	148,382
Habitat quality index	97,260

credit) that will increase the social welfare (credit) enough to offset the welfare decrease due to the forest fire (debit). Although used to value an environmental improvement instead of avoiding a loss, the questionnaire followed a structure similar to the one used to estimate the debit. The interim loss due to the forest fire was described, and off-site afforestation that would be implemented to compensate for the interim loss was proposed. The cost of this compensatory action would be about €60 per household per year for 10 years, increasing every year with inflation (taken from the first CV used to estimate the debit).

The size of the area where black pines would be planted as compensation varied across the sample (an area of 10% of the damaged site, followed by 20, 30, 50, 70, and 100%). By fixing the monetary bid and varying the environmental change, the minimum size of afforestated area that people require to offset the €60 welfare loss due to the original forest fire was estimated.

In late 2007 and early 2008, the questionnaire went through multiple focus groups and a pilot testing phase. The full survey was implemented in the Spring of 2008. The sample size and selection were similar to that used for the debit exercise. Interviews were also in-person. The mean duration of an interview was 13 min.

Like for the debit estimation, a standard statistical procedure (see, e.g., Hanemann and Kanninen 1999) was used to estimate the necessary amount of compensation in terms of the area of afforestation necessary to compensate for the damage (expressed as a percentage of the originally burned area). The result show that respondents wanted the afforestation area to be 33% of the damaged area, on average.

An interpretation of this result is that under a value equivalency analysis, a forest loss similar to the BABE loss, had it taken place in early 2008, would require a full primary restoration plus an additional 33% of the area damaged as off-site afforestation (for compensatory remediation to address the interim losses). In other words, 1 surface unit of black pine lost due to forest fire requires, in value-to-value terms, 1.33 surface units of black pine afforestation, 1 on-site and 0.33 off-site. Translated into hectares of compensatory remediation, 33% of the original BABE estimated area, which was of 25,000 ha, results in 8,250 ha of off-site afforestation. Compared to the number of hectares needed from the other metrics (Table 11.9), the value-to-value approach requires four times less than the area estimated using the number of trees metric in a resource-to-resource approach.

11.5.2 Scaling Fire Prevention

Scaling for the fire-prevention plan was only calculated for the four non-monetary metrics. The results are shown in Table 11.10. Noticeably, the very large size of the remediation option that would be required for some of the metrics to compensate the interim loss may preclude a direct application of the fire-prevention compensatory remediation. The conclusion is that the fire-prevention compensatory option can be excluded as a valid option for a full compensatory remediation measure.

Table 11.10 BABE Forest Fire—Scaling the fire prevention remediation plan

Metrics	Size of compensatory remediation (10^6 ha)
Number of trees	6.11
Forested area	8.94
Biomass	3.63
Habitat quality index	10.34

11.6 Sensitivity Analysis

A sensitivity analysis of model metrics was performed to understand how uncertainty in some of the input parameters may affect the size of the off-site afforestation remediation plan. Relative sensitivity δC of the size of the compensatory remediation to changes in an input parameter p, for a given metric, was defined as

$$\delta \mathrm{C} = \frac{\Delta \mathrm{C}}{\mathrm{C}} \cdot 100$$

where ΔC denotes variations in the area when the input parameter is modified. Changes in the input parameters were introduced one at a time—the parameters were varied $\pm 20\%$ of their nominal value.

Area of forest fires, tree mortality, and percentage of natural forests were selected as the most relevant parameters to be considered in a sensitivity analysis. Relative sensitivity was also measured for the four metrics when the original definition of a 'tree' was modified from 75 to 50 mm DBH. Results are shown in Tables 11.11a, b, c and d.

The results presented in these tables are interpreted as follows. Positive sensitivity implies that the size of the remediation increases when the value of the parameter tested increases. Interestingly, the relative sensitivity to changes in the percentage of natural fires that were included in the calculations is very low. This makes the results presented in this work applicable to cases in which an operator may be liable for a percentage of fires that differs from the nominal value of 10% adopted in this study. The results are also not very sensitive to the variations in the area of future forest fires. This is an indication that this work may also be applicable in future scenarios of higher average temperatures (and therefore higher risk of forest fires) in the Mediterranean area, that can be expected with future climate change. The metric 'number of trees' is the most sensitive of all metrics to a change in the definition of a tree from 75 to 50 mm DBH. This is to be expected since counting trees directly depends on what a 'tree' means. It is no surprise that it is possible to obtain a relative sensitivity close to 40%. The relative sensitivities for the other three metrics are also large. Table 11.11 indicates that including smaller trees in the definition reduces the size of the compensatory remediation plan.

Table 11.11 BABE Forest Fire

(a) Relative sensitivity (%) to changes in the area of future forest fires	
Number of trees	2.1
Forested area	2.0
Biomass	3.9
Habitat quality index	2.4
(b) Relative sensitivity (%) to changes in tree mortality probability	
Number of trees	10.7
Forested area	3.4
Biomass	5.5
Habitat quality index	1.6
(c) Relative sensitivity (%) to changes in the percentage of natural fires	
Number of trees	1.0
Forested area	0.7
Biomass	1.2
Habitat quality index	0.8
(d) Relative sensitivity (%) to changes in minimum DBH of a tree	
Number of trees	40.3
Forested area	24.8
Biomass	6.7
Habitat quality index	6.6

11.7 Cost Estimation

11.7.1 Off-Site Afforestation

Costs were evaluated differently based on whether the areas to afforest were public land or private land. In both cases, costs would be paid for by the operator. In the first case, only the following items were considered:

- Soil preparation of 50 cm depth by ripping with a caterpillar tractor;
- Large-scale purchase of black pine seedlings;
- Transport of seedlings to the sites; and
- Manual seedling planting (including technicians and special equipment).

Costs were estimated using the price lists from a large local reforestation and silviculture company. These numbers should agree well (within reasonable limits) with those from similar companies in Catalonia and elsewhere in Spain. Relatively high contingency costs of 20% are allowed to account for unsuccessful afforestation due to, for example, unfavorable meteorological conditions. The total cost of reforesting/afforesting 1 ha is shown in Table 11.12. All prices provided are in Euros in real values of 2007.

Table 11.12 BABE Forest Fire—Costs of reforesting/afforesting one hectare of public land

Item	Price (€)	Price per hectare (€)
2-year seedling	0.6	900
Soil preparation per km	73	283
Transport and planting	864	864
Total		2,047
Total + 20% contingency		2,456

The costs and funding strategy for the fire prevention plan was assumed to be similar to that of the Common Agricultural Policy of the European Community, whereby owners receive an annual subsidy for 15 years after the afforestation. However, costs were to be paid for by the operator, not by the European Community or any state agency. Those subsidies per hectare were included into the total cost, shown in Table 11.13. A contingency cost of 20% was also included.

A total of 20,000 out of 128,000 ha found in the GIS analysis for suitable areas for afforestation was public land or run by state agencies. Costs for public and private land were then calculated accordingly for each metric. Results are shown in Table 11.14 in Euros in real values of 2007. Prices were computed assuming planting rates were scaled such that afforestation always took 10 years to be completed.

11.7.2 Fire Prevention

A full-scale implementation of a fire-prevention plan involved highly complex cost estimations. Given that fire prevention actions generate very low credits, the costs of these actions were not estimated.

Table 11.13 BABE Forest Fire—Costs of reforesting/afforesting one hectare of privately owned land

Item	Price (€)
Planting costs	1,226
Total annual premium (15 years)	2,170
Total	3,396
Total + 20% contingency	4,075

Table 11.14 BABE Forest Fire—Total costs for each metric

Metric	Price (€)
Number of trees	114,871,507
Forested area	254,688,722
Biomass	572,314,258
Habitat quality	363,980,185

11.8 Monitoring and Reporting

The equivalency analyses described here relied on the use of appropriate forest simulation models to determine the type and amount of compensatory remediation action to be provided to compensate for environmental damage following injury. The implementation of simulation models could greatly benefit from better and/or up-to-date datasets from monitoring of how both the burned and the unburned forests change over time. Table 11.15 shows such a monitoring approach. Depending on the type of process to regularly measure or observe, different monitoring time intervals are proposed. Monitoring costs were not estimated. Reports on the recovery trajectory and possible (if any) actions to correct for deviations should be made public every five years.

11.9 Discussion and Conclusions

11.9.1 Estimation of Debit in the Value Equivalency Analysis

In a value equivalency context, the debit could be estimated by benefit (or value) transfer or by a specially designed valuation exercise. Debit and credit valuation could be presented to respondents in the same questionnaire. In this case study, two separate surveys are conducted, first for the debit then for the credit. Given that remediation options will take place over a long term, if the valuation study uses periodic payments of this time period, it is advisable to specify whether payments will vary with inflation or not as future income could vary in any event. As presented here, it was announced that the 10 annual payments would vary according to inflation.

11.9.2 Compensation of Debit

The recommended ecological compensatory remediation plan consists of the off-site afforestation of other suitable areas in Catalonia. Several considerations

Table 11.15 BABE Forest Fire—Monitoring and data collection program for *P. nigra* trees

Item	Time interval
Seedling survival and growth	Yearly
Onset of reproduction	From 20 years of age, every 5 years
Tree diameter growth	Yearly
Changes in fire regime	5 years

could enter the decision-making processes that were not included in this case study, including the availability of enough seedlings and varying market prices.

The conclusion that can be drawn from the analysis here is that metrics used to quantify the damage affect the amount of remediation needed. The most preferred metrics are likely to be total number of trees and total forested area. It is easiest to achieve total compensation using the number-of-trees metric. On the other hand, the amount of compensatory remediation to be implemented for the total forested area will be larger when the other two metrics are considered. This reveals the limitations of using a single metric in describing damage and recovery of the BABE forest.

The value-to-value application from the credit exercise illustrated how the remediation program scaling could be implemented based on a choice contingent valuation approach. With this approach, instead of varying the monetary bid amount, the amount of compensation varies among subsamples. In this way, the mean of the minimum environmental compensation required to offset the welfare loss can be estimated. The metric used in the application was hectares of new black pine forests planted off-site, in a given location, size of which was expressed as the percentage of the damaged area. It was found that as compensatory remediation for interim losses, the damaged forest area was to be compensated by a full primary remediation and by an additional 33% of off-site black pine afforestation in a nearby location.

There is a large difference in the required amount of compensation estimates between the value equivalency and the resource or habitat equivalency applications in this case. The value equivalency approach returns a significantly lower amount of remediation. There can be multiple reasons for such a divergence. One is the usual and, to some extent, inevitable simplification of the ecological change explanation in a questionnaire. This simplification may underestimate the description of damages and thus the compensatory remediation in some instances, even though in some cases the same reason could lead to the opposite situation of overestimation. A second reason can be found on the ecological side. In this case study, the definition of a tree used in the resource equivalency analysis implies that the afforestation renders no credit until almost 40 years after planting. It is likely that younger forests in the on-site restoration and in the off-site afforestation area count for something more than zero in respondents' mind. A third reason is about expectations. There is no need for ecological analyses and social perceptions, on which value equivalency is based, to produce the same results and, indeed, differences could result in either direction.

11.9.3 Natural Versus Accidental or Provoked Forest Fires

Although numbers may vary depending on year and region, approximately 10% of all forest fires in Catalonia have a natural origin (i.e., lightning). The remaining 90% are due to accidents (e.g., sparks from power lines), deliberately started, or are of an unknown cause. In this study only natural forest fires were included both in the baseline and in the compensatory remediation calculations, since the operator cannot be made liable for fires that are not caused by their operations. Moreover, to further check the dependence of the total interim loss on the percentage of natural fires affecting the forest, we performed the same analysis when 100% of all forest fires were included. The result was that although both the baseline and primary remediation differed greatly, the interim loss was less affected by the total amount of fires. That is, fires affect both baseline and primary (and compensatory) remediation in such a way that their effects partially cancel out.

11.9.4 Limitations and Further Improvements

11.9.4.1 Simulation Models

Several simulation models were used to predict the dynamics of a Mediterranean forest. Indeed, predictions about the temporal evolution of forest structural parameters and other ecological indices must be treated with care. In building simulation models, one usually makes a number of assumptions that, on the one hand, simplify the algorithms and make it possible to answer a set of questions within a reasonable time and with relatively limited budgetary and computational resources. On the other hand, those simplifications may give rise to significant errors in mid-term and, especially, long-term predictions. It is therefore advisable to test and validate the simulation algorithms that are used in the study.

11.9.4.2 Inclusion of Smaller Trees

In the present analysis, only stems with diameters at breast height of greater than 7.5 cm were defined as trees and included in the calculations. When that definition was revised to include diameters of 5.0 cm, the results changed, even though only the number-of-trees metric was strongly affected. In general, a scaling factor could be introduced so as to account for smaller stems in some of the other three metrics. Such a factor could in fact be different for different metrics, namely:

- Trees could be weighted by the basal area they occupy, so that smaller stems are still accounted for (although the contribution of smaller stems to total basal area is predictably small);
- Total forested area may take account of the cover provided by smaller stems; better allometric relations between diameter and canopy cover would be required;
- A new habitat-quality metric could be devised to take into account, as a new factor, the potential production of cones depending on tree diameter, since trees of smaller diameter also produce cones, albeit at a much lower rate; and

- The presence or absence of birds could be used as a new metric to quantify the quality of the damaged ecosystems. The wealth of information about birds and their nesting habits in Catalonia (e.g., Atles dels ocells nidificants de Catalunya, 1999–2002) may make this approach possible. Birds may show different nesting and feeding behaviours depending on the size of the trees, which could be factored into this new metric.

As pointed out in the sensitivity analysis, the addition of smaller trees to the calculations drastically changed the number of trees and the forested area metrics, so as to measurably reduce the size of the required remediation option. Biomass and total habitat-quality metrics, on the other hand, were less sensitive to the addition of smaller trees.

11.9.4.3 Datasets

The main datasets used in elaborating the simulation model were the second and third Spanish forest inventories. Finalisation of the fourth Spanish inventory, to be published during the next decade, will make it possible to follow up on the evolution of the different stands during a much longer period of time. The simplified numerical model with which the dynamics and evolution of the damaged BABE forest were explored in the present analysis could then be improved in many ways. One would expect better growth and mortality parameter estimates to be computed from three consecutive forest inventories instead of two, as was done in this study. Diameter growth estimates should also benefit from the availability of new data. These changes should lead to better medium- and long-term predictions about forest structural parameters and, hence, to improved estimates of the metrics.

Further improvements to the predictions put forward by the simulation models may come about from the study of recently planted areas. Growth and mortality of black pine seedlings and juveniles under varying local conditions were calculated in this case study from relatively scarce field and laboratory experiments. Indeed, it would be desirable to develop a careful monitoring and data-collection plan in order to introduce new and better local experimental data from the plantations into the simulation model. These new data, together with improved simulation algorithms, would generate more accurate predictions of the evolution of the metrics.

11.9.4.4 New Species to Be Included

Although the pre-fire BABE forest contained a large proportion of pure or almost-pure black pine stands, there were other tree species with an important presence in the area, which were not incorporated into the analysis above. Those species included, among others, several species of *Pinus* (e.g., *P. sylvestris, P. halepensis*) and of *Quercus* (e.g., *Q. ilex, Q. cerrioides*), which may play a role in shaping the future dynamics of the forest through interspecies competition. The different responses of those trees to competition and water or light limitations will likely determine an evolution of the forest that is different from the one explained here. Nevertheless, the methodology applied to examine the ecological remediation of the 1994 BABE fire will hold true.

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Appendix A: Simulation of the Recruitment of Black Pine Trees in Unburned Forests

Processes affecting tree stands were modeled as deterministic or stochastic functions that in turn depended on stand basal area and/or tree diameter. Those functions determined the temporal evolution of the simulated forest and were empirically determined from the Spanish Inventario Forestal Nacional II (1989–1990) and III (2000) and from the Inventari Ecològic i Forestal de Catalunya. The presence of non-dominant tree species was discarded in the calculations. Consequently, the model behaves as a truly monospecific black pine forest simulation.

The area of study was divided into 1-ha tree plots. The algorithm separately followed the evolution of the cohorts of trees with the same DBH within those tree stands and calculated the four metrics and the area burned per year. Unless so stated, metrics did not consider trees whose diameter at breast height was smaller than 7.5 cm. Climatic variations and their impact on future fires, forest growth, and forest dynamics were not included in the model.

Initially there were numerous parameters to set (typical values are shown in Table 11.16). Model parameters were computed both from field data and from a comparison of 2nd and 3rd forest inventories and field data as follows:

- DBH growth was calculated as a cubic polynomial on DBH for DBH larger than 75 mm. Smaller trees were assumed to reach that DBH in 15 years.
- Tree height and tree canopy diameter were represented by an allometric function, where DBH was the explanatory variable. Parameters were derived from field data.

Table 11.16 BABE forest fire—free parameters in model A

Parameter	Value
Number of simulations	100
Forested area in Catalonia (ha)	1,604,243
BABE area (ha)	25,000
Age of seedlings at a height of 1.3 m	15 years
Discount rate (%)	3%
Number of years to simulate	100

- Forest ingrowth, which is defined as the number of trees that periodically grow into the smallest measured size class of a forest stand, was computed for the following basal areas classes (in square meters): [0, 10), [10, 20), [20, 30), and [30, ∞).
- Tree mortality probability was calculated jointly for each basal area class (such that mortality in denser plots would increase due to competition) and DBH class (such that mortality rate increases when trees are either very small or very large). DBH classes were defined for tree diameters within the following size intervals (in millimeters): [75,125), [125, 225), [225, 425), and [425, ∞).

A single run of the model consisted of 100 time steps, which corresponded to a time interval of 100 years. Initially, a 25,000-ha forest with the same average initial structure (i.e., tree size and age) as the unburned forest was created. The algorithm then proceeded as follows at each time step (see Figure 11.7):

1. Trees in a cohort grow in diameter depending on their DBH.
2. A fraction of those trees may also die depending on their DBH and basal area.
3. Ingrowth takes place depending on basal area.
4. Conditions for forest management practices to be applied are evaluated and implemented if necessary.
5. Forest fires of random size and frequency may affect the simulated forest (see Appendix B).
6. Reforestation/afforestation strategies may be applied if required.
7. Metrics are calculated for trees with DBH larger than 75 mm.

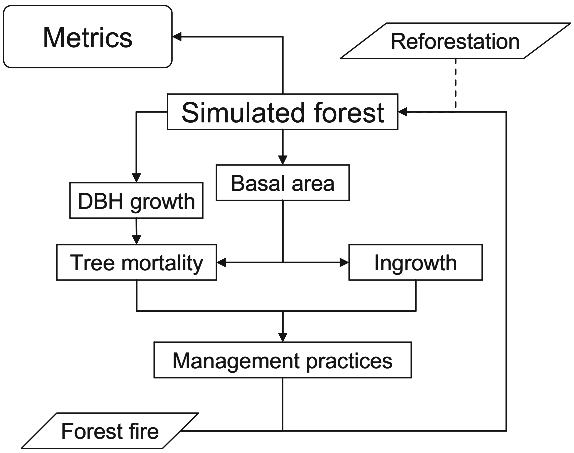

Fig. 11.7 Flowchart of the forest model

Appendix B: Simulation of Future Forest Fires

The three important parameters to consider when modeling fires are:

- Frequency (how many fires have there been per year);
- Size (larger fires will likely be less common than small ones); and
- Location (in general, fires will not be exactly the same as the BABE fire, nor will they burn exactly the same area).

A complete fire propagation model, in which an explicit dependence on meteorological conditions, local topography, and land cover are explicitly introduced, was beyond the scope of this case study. Instead, a simple and very graphic approach to forest fire modeling was adopted. The total forested areas of Catalonia (a total of 1.6 million ha) are analogous to a circular area of 71,459-meter radius, at the center of which is drawn another circular area of 25,000 ha (8,921-meter radius), equivalent to the BABE area (Figure 11.8). Datasets for forest fires were taken from Díaz-Delgado and Pons (2001) for the period 1975–1998 in Catalonia.

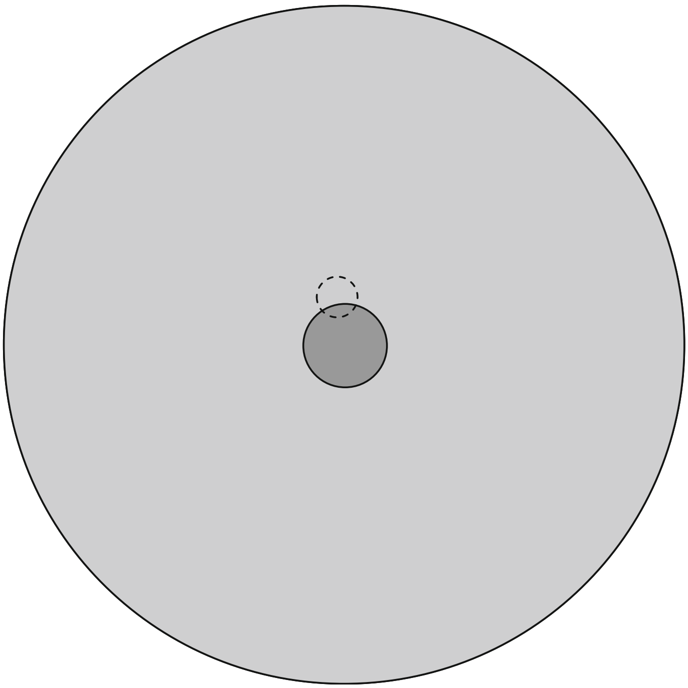

Fig. 11.8 Schematic of the forest area in Catalonia. *Note* The outer circle represents the total forested area of Catalonia. The smaller, darker circle within this, corresponds to the BABE forest. The figure is a proportionate reflection of the burned and total areas. The dashed circle intersecting the central disk corresponds to a 5,770-ha fire, of which 1,300 ha have affected the BABE area in this example

Those data included information about frequency and extent. The stochastic simulation then proceeded as follows: the algorithm picked one year's worth of data at random from the 1975–1998 datasets and distributed those fires at random over the simplified circular area. Each fire from the chosen dataset was also assumed to be circular and may or may not intersect the BABE area. If d is the distance between the center of the two circles, R is the radius of the circular BABE forest, and r is the radius of a circular fire, then the area A of the intersection between the two circles was given by:

$$A = r^2 \cdot \cos^{-1}\left(\frac{d^2 + r^2 - R^2}{2dr}\right) + R^2 \cdot \cos^{-1}\left(\frac{d^2 + R^2 - r^2}{2dR}\right) - \frac{1}{2}\sqrt{(-d + r + R) \cdot (d + r + R) \cdot (d + R - r) \cdot (d + R + r)}$$

If the two circles did not intersect (i.e., the square root is imaginary), it was assumed that the fire did not affect any portion of the BABE area.

References

Adamowicz, W., Louviere, J. & Swait, J. (1998). *Introduction to Attributed-Based Stated Choice Methods*, Final Report to the Resource Valuation Branch of the NOAA Damage Assessment Center, Advanis.

Bishop, R., Breefle, W., Rowe, R., & Wytinch, S. (2000). *Restoration scaling based on total value equivalency: Green Bay natural resource damage assessment final report*. Boulder CO: Stratus Consulting Inc.

Bolòs, O., Vigo, J., Masalles, R. M., & Ninot, J. M. (1993). *Flora Manual dels Països Catalans*. Barcelona: Editorial Pòrtic.

Burriel, J. A., Gracia, C., Ibàñez, J. J., Mata T., Vayreda J. (2000–2004). *Inventari Ecològic i Forestal de Catalunya*. CREAF, Bellaterra. ISBN de la sèrie: 84-931323-0-6.

Díaz-Delgado, R., & Pons, X. (2001). Spatial patterns of forest fires in Catalonia (NE Spain) along the period 1975–1995. Analysis of vegetation recovery after fire. *Forest Ecology and Management, 147,* 67–74.

Dirección General para la Biodiversidad. (2007). *Los Incendios Forestales en España. Decenio 1996–2005*. Ministerio de Medio Ambiente, España ().

Espelta, J. M., Retana, J., & Habrouk, A. (2003). *An economic and ecological multi-criteria evaluation of reforestation methods to recover burned Pinus nigra forests in NE Spain*.

European Commission (2007). *Interpretation manual of European Union habitats EUR 27*, Brussels: European Commission, DG Environment.

Gracia, C., Burriel, J. A., Ibàñez, J. J., Mata, T., & Vayreda, J. (2002). *Inventari Ecològic i Forestal de Catalunya*. CREAF, Bellaterra: Obra completa.

Hanemann, M., & Kanninen, B. B., (1999). The statistical analysis of discrete-response CV data. In Bateman, I. J., & Willis, K. G. (eds.) *Valuing Environmental Preferences. Theory and Practice of the Contingent Valuation Method in the US, EU, and Developing Countries*. Oxford: Oxford University Press.

Ibáñez, J. J., Burriel J. A., Mata, T., Torralba, J., Castro, F. X., & Canyameras, E. (2007). Gestión agrícola y prevención de incendios forestales. *4th Internacional Wildland Fire Conference*, 14–17 May, Sevilla, Spain.

Molowny-Horas, R., Comas, L., Retana, J. (2007). Modelo de simulación forestal de regeneración de *Pinus nigra*. II Reunión del Grupo de Trabajo de Modelización Forestal de la Sociedad Española de Ciencias Forestales, 9–11 May 2007, Jarandilla de la Vera, Spain.

Ordóñez, J. L., Molowny-Horas, R. L., & Retana, J. (2006). A model of the recruitment of *Pinus nigra* from unburned edges after large wildfires. *Ecological Modeling, 197,* 405–417.

Peix i Massip, J., (1999). *Foc Verd II: programa de gestió del risc d'incendi forestall*. Direcció General del Medi Natural, Barcelona.

Pons, X. (2007). *Miramon*. CREAF: Sistema d'Informació Geogràfica I Software de Teledetecció. Bellaterra. ISBN 84-931323-5-7.

Retana, J., Espelta, J. M., Habrouk, A., Ordonez, J. L., & de Sola-Morales, F. (2002). Regeneration patterns of three Mediterranean pines and forest changes after a large wildfire in northeastern Spain. *Ecoscience, 9*(1), 89–97.

Rodrigo, A., Retana, J., & Picó, F. X. (2004). Direct regeneration is not the only response of Mediterranean forests to large fires. *Ecology, 85,* 716–729.

Terradas, J. (1996). El foc en un context mediterrani. Ecologia del Foc. Edicions Proa, Barcelona. J. Terradas (editor).

Thuiller, W., Vayreda, J., Pino, J., Sabate, S., Lavorel, S., & Gracia, C. (2003). Large-scale environmental correlates of forest tree distributions in Catalonia (NE Spain). *Global Ecology and Biogeography, 12,* 313–325.