NEW GIS DEVELOPMENTS IN MOUNTAIN PROTECTION FORESTS ZONING AGAINST SNOW AVALANCHES AND ROCKFALLS

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ABSTRACT

Forests can play a significant role in protection against natural hazards and risks in mountain areas. To maintain the protective function, an adapted silviculture must be applied to these forests. Due to the financial restrictions affecting this management, it is important to map the protection forests and to define priority areas for forest silvicultural interventions. Geographic Information Systems (GIS) are very useful for geospatial data analysis and spatial modeling. Several geographic data, such as Digital Elevation Model (DEM) or coverages such as built-up areas, roads and forests, are required to localize forests with a protective role using GIS. Algorithms, implemented for ArcInfo Workstation or GRASS GIS have been developed to localize potential release areas and maximal runout envelop of avalanches and rockfalls. A GIS data crossing allows to determine forest areas concerned by each hazard. Then, socio-economic data are added into the model to define priority levels. Priority codes express the emergency for forest actions. The final result of the GIS model is a map of all protection forests classified by priority intervention zones.

Key Words: Zoning, Protection forests, Mountain hazards, GIS, Rockfall, Avalanche

INTRODUCTION

Society considers forests as an essential part of natural environment. Forest has several functions such as wood and timber production, food resource or biodiversity. Nowadays, people have more and more spare time and the forest acquires new functions: tourism, outdoor activities and landscape protection. In mountain areas, forests have also a very significant role: the protection against natural hazards. These forests, called protection forests, can partially or totally control some natural hazards such as erosion, floods, rockfalls or avalanches (Renaud *et al.*, 1994). The sustainability of hazard control by forests depends on forest stability: for instance, an old forest is less stable and its protective efficiency decreases through time. Foresters have to adapt the silviculture to maintain or increase the protective role of these forests. In France, the *Guide de Sylviculture de Montagne* (Cemagref *et al.*, 2006) defines guidelines, based on natural cycle, for mountain protection and production forests in the northern Alps. To apply these rules, it is important to know the distribution of protective forests and to define priority zones for forest interventions. An Interreg Project, called "Interreg Forêt de Protection (IFP)" started in 2008 between France and Switzerland to carry on applied research on protection forests. One of the tasks of this project, presented in this

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paper, is to develop a Geographic Information System (GIS) method for mapping protection forests.

FORESTS AND NATURAL HAZARDS

Mountain areas are particularly exposed to natural hazards such as avalanches, rockfalls, landslide, erosion or floods. The IFP project focuses on the three first hazards. Depending on the location of forests: departure, transit or stopping zone; the protective role will be different (Berger *et al.*, 2003). Table 1 presents the forest effectiveness to control natural hazards:

Table 1: Forest ability to control natural hazards

Natural hazard	*Location*	Forest control admitted
Avalanches	Departure zone	Yes
	Transit and stopping zone	No
Rockfalls	Departure zone	Yes
	Transit and stopping zone	Yes
Landslides	Departure zone	No
	Transit and stopping zone	No

The protection can be divided into two categories: active and passive protection. The active one prevents the hazard from occurring. It is the case of forests situated in departure zone: forests stabilize the snow layer and prevent rocks from moving thanks to the root system. The passive protection reduces the impact of a hazard on the stakes. Forests located in the transit zone of a rockfall offer a passive protection.

This paper will focus on the GIS development for the localization of the protection forests against snow avalanches and rockfalls.

MATERIALS AND METHODS

GIS data

A GIS is a system which includes mapping software and its application to remote sensing, land surveying, aerial photography, mathematics, geography, and tools that can be implemented within GIS software. It is a powerful tool for geospatial data management and spatial modeling. In simpler terms, GIS is the merging of cartography and database technology. For the study, two GIS softwares have been used: ArcInfo 9.2 and GRASS GIS 6.4.0svn. Our aim was to develop an automatic method for mapping protection forests. First, several scripts have been written to localize start zones and maximal runout envelop of avalanches and rockfalls. Then, complementary scripts have been developed to map protection forests using maximal runout envelops and the localization of socio-economic stakes. ArcInfo scripts are implemented in Arc Macro Language (AML) for ArcInfo Workstation, and GRASS scripts are written in Python.

Data used in this study can be grouped into three main types: (1) Information on rockfall and avalanche events, (2) Digital Elevation Model (DEM) for the simulations and (3) coverages for mapping process.

1. Informations on the past events were provided by the French avalanche location map (Carte de Localisation des Phénomènes d'Avalanche, CLPA) and by standing investigation of avalanches (Enquête Permanente des Avalanches, EPA) for avalanches. Concerning rockfall events, the natural hazards map used in the Risk Prevention Plan (Plan de Prévention des Risques, PPR) is a useful source of information. These documents list and map the geographic extension of all the known phenomena. To do so, the practitioner carries out investigations in archives, studies existing maps, makes field observations, and gets information from the survey carried out by the population (Berger and Rey, 2004). These data have been used to calibrate and to validate our models, especially for the energy line model and for the maximal propagation area of events.
2. Digital Elevation Model (DEM) is a raster datum needed for the simulations of the maximal runout envelop of avalanches and rockfalls. DEMs from the BD TOPO of the French National Geographic Institute (IGN) with a resolution of 25 m × 25 m were used. DEMs are grid data and represent the ground surface topography from a locational perspective (dividing space into discrete units called cells) (ESRI, 1991). Each cell has an altitudinal value. DEMs are useful for topographic analyses like slope, curvature and relief calculations (Clouet and Berger, 2009).
3. GIS coverages include forest areas and stakes. Forest coverages are produced by the French National Forest Inventory (NFI or IFN in French) and by the French National Forest Office (ONF). Theoretically, dendrometric characteristics like density or species of the stands are joined to the GIS data. Stakes are all human facilities: buildings, industries or public transport. These coverages, from the BD TOPO are also built by the French National Geographic Institute (IGN). A map crossing is needed between maximal runout envelops and forests to localize those concerned by one or several hazards. Then stakes are analysed to graduate the emergency of silvicultural actions.

GIS process for protection forest mapping

The GIS process is divided in 4 steps, which can be summarized in the Fig. 1.

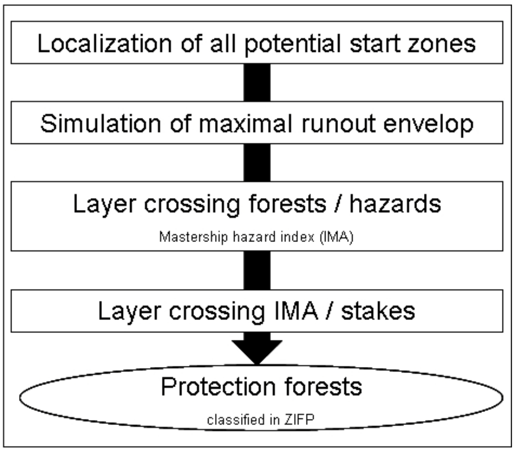

Fig. 1: GIS process integrated in the model

Simulations of potential start zones (Fig. 2)

A GIS model has been written for the localization of avalanche and rockfall potential starting zones. For rockfalls, the model is based on slope analysis. A calculation of slope is made from the DEM and a slope criterion is chosen to draw rockfall start zones: all cells with a higher value than the threshold are qualified as a potential release zone. The threshold slope α has been defined in the European project Provialp (Cemagref and Arpa, 2008) and depends on the DEM resolution, as in Eq. (1):

$\alpha = 55^{\circ} \times RES^{-0.075}$, where RES is the resolution of the DEM (1)

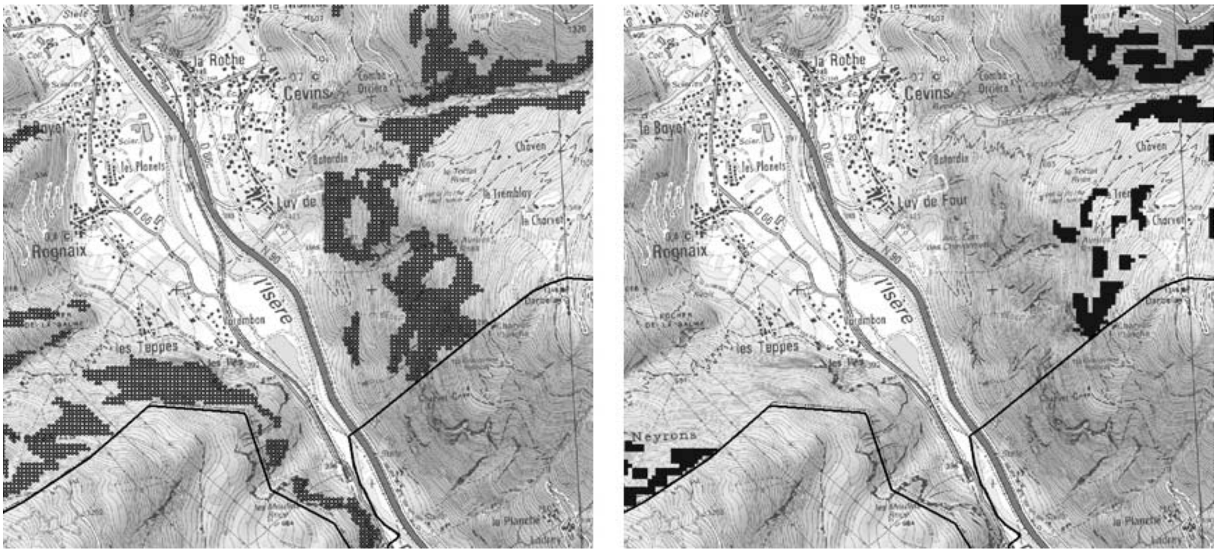

Fig. 2: Potential start zones for rockfalls (left) and avalanches (right)

The DEM resolution used for this study is 25 m × 25 m, so the threshold slope is 43° (Cemagref and ARPA, 2008).

Avalanche start zones are more complex, because 3 analyses from the DEM need to be made: a slope calculation, a curvature calculation and an altitudinal criterion. All cells with a slope between 28 and 55 degrees, with a convex surface and with an altitude higher than 1000 meters are considered as snow avalanche potential release zones (Berger, 1997).

Simulations of maximal runout envelops

Potential starting zones for rockfalls and avalanches have been localized. The maximal propagation from each of these points was simulated using a statistical approach and the concept based on energy line models. A second GIS model has been therefore written, based on the Energy Line model (Heim, 1932), which allows to relate rockfall runout envelops to slope angles. The maximal spread of a block is determined by intersecting the ground and an imaginary line drawn from its start point with an angle β (Fig. 3). For the simulations, a value of 32° was used for β. This value has been calibrated from rockfall experiments carried in a real site in Vaujany, Isère, France (Dorren *et al.*, 2005). In the model, the maximal spread is made with a visibility analysis in the steepest slope direction (aspect function in ArcInfo, r.slope.aspect function in GRASS GIS), with an upper vertical limit of 32° for the scan. The result is the global envelop of all the area concerned by rockfalls (Fig. 3).

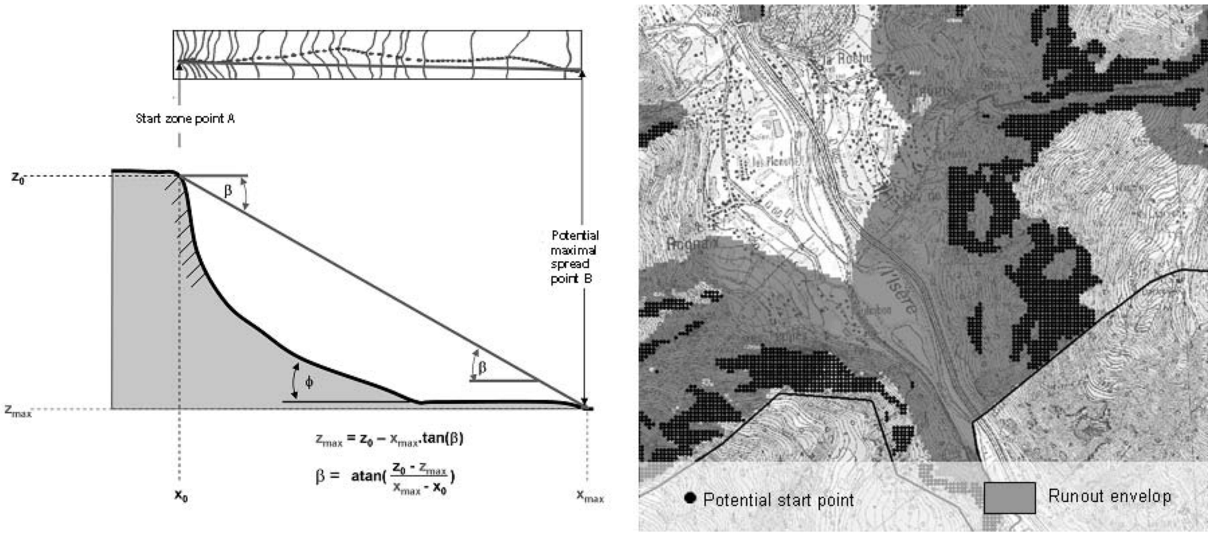

Fig. 3: Energy line principle and maximal spread for rockfalls

Once again, the GIS model of avalanche spread is more complex, but is also built with the Energy line model. According to this principle, an avalanche can go from a start point A to a point B with an angle α, depending on a second angle β. This β is the angle made between the point A and the first point where the ground slope is equal to 10° (Fig. 4). The relation between α and β has been calibrated in Chamonix Valley, France, with a high precision DEM (laserscan data). A profile has been drawn on each of the 103 known avalanches on the CLPA. From each profile, the value of α and β has been determined and the statistical relation between these two data is the one given in the Eq. (2):

$\alpha = 0.979\beta - 0.996$, $R^2 = 0.8964$ (2)

From all potential start points, a flow analysis (flow direction and flow accumulation functions in ArcInfo, r.flow and r.drain functions in GRASS GIS) is made to draw the avalanche path. Then, a slope analysis maps all cells where the slope is lower or equal to 10°. In that way, β is calculated. Then Eq. (2) is applied to determine α and the maximal runout envelop of all avalanches (Fig. 4).

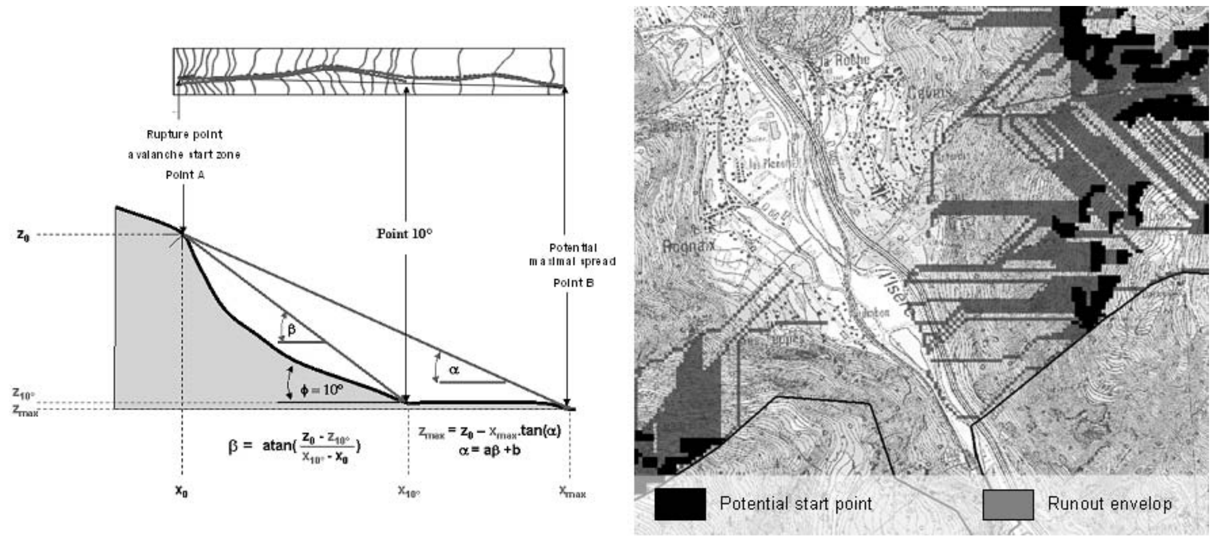

Fig. 4: Energy line principle and maximal spread for avalanches

Layer crossing forests – hazards

At this step of the analysis, the main hazards concerned by the Interreg project, avalanches and rockfalls, are now characterized: all potential start points and maximal runout envelops have been mapped. The aim of the study is to map all protection forests. So, a GIS data crossing between maximal envelops and IFN forest coverages is performed to determine forest areas concerned by hazards. A hazard mastership index (IMA in French) is associated to each of these new forest polygons to express the ability of the forest to mitigate natural hazards. This index depends on the type, the frequency, the intensity and the localization of hazards, and on dendrometric characteristics such as density, basal area, crown canopy, stability, or species of the stand. Forest parameters come from field surveys, from photointerpretation or from laserscan data: tree height, density and diameter can be calculated (Clouet and Monnet, 2009). The hazard mastership index ranges from 0 (no control) to 6 (high control) and is a relative quotation to compare all stands between them. A quotation of 6 doesn't mean the stand controls a hazard 6 times better than a stand with a index of 1, but only that an index of 6 offers a better control than 1. Table 2 shows the codification for rockfalls, with blocks of a volume lower than 5 m^3. A similar table for avalanches is also available.

Table 2: Hazard mastership index for rockfalls

		Stand density (N/ha)		
	Basal area (m²/ha)	<250	250 – 500	>500
Start point in the forest	<25	1	3	4
	>25	2	5	6
Start point upstream the forest	<25	0	1	3
	>25	0	4	5

The final step consists in an analysis on the socio-economic issues concerned by hazards, and to define priority levels expressing the emergency for silvicultural actions.

Layer crossing hazard mastership index – stakes

The previous step allowed localizing and qualifying the protection role of all forests concerned by hazards. These forests have been marked with an index to show their ability to control the hazard. A forest is considered as a protection forest only if it protects society and facilities from hazards. A pertinent analysis on all stakes is needed to classify them, because a factory or a shopping centre is a much more important facility than an isolated barn. All items of all stake coverages, from the BD TOPO of the French National Geographic Institute (IGN) have been marked from 0 to 3, depending on its type and its size. 0 means a very low stake level and 3 a high level. Stakes have been divided into 9 groups: dwelling, communication network, electrical, gas and water systems, tourism, industry and store, agriculture, forest, cultural heritage and public facilities. All of these groups have been classified into 4 levels of quotation. For example, an isolated building has a quotation of 1, and a group of 10 houses is 3. There isn't any dwelling with a quotation of 0. Concerning tourism, a hotel has a quotation of 3 and a hiking trail or a canoe route is 0.

When all stakes have been marked, a GIS data cross is made between them and forest data. This analysis gives informations on the priority or the emergency for forest actions: for instance, a factory below an old unsteady forest has a higher priority level for forest interventions than the same factory below a "perfect protection forest". Table 3 summarizes the priority levels, from stake quotation and forest stability:

Table 3: priority level for forest interventions

Stake quotation	*Forest stability*	**Priority level**	
0 (very low)	Stable	-	Very low
	Unsteady	-	
1 (low)	Stable	+	Low
	Unsteady	+	
2 (medium)	Stable	++	Medium
	Unsteady	++	
3 (high)	Stable	++	
	Unsteady	+++	high

Finally, a last GIS cross is performed between the priority levels and the forest polygons for which a hazard mastership index classification has been proceeded. A final code, called Priority Zones for silvicultural interventions (ZIFP, Zone d'Intervention Forestière Prioritaire in French) is allocated to forest polygons having a protective role. This index allows to determine prioritized compartments for forest interventions. Table 4 explains the principle of this last analysis and the ZIFP code:

Table 4: ZIFP classification

	Priority level			
Hazard mastership index (IMA)	+	++	+++	**Recommended action**
0 and 1	1	1	1	Civil engineering
2	2	2	3	Civil engineering and forest actions
3	2	3	4	Improvement and/or forest management
4	3	4	5	
5	4	5	6	
6	5	6	6	

The final result of the GIS model is a map of all protection forests classified by priority intervention zones: some of them fulfill their protection function and no intervention is required for the next 50 years, the management of others just needs to be adapted. At the opposite, several forest areas can't ensure a good enough protection for people and civil engineering is needed.

RESULTS

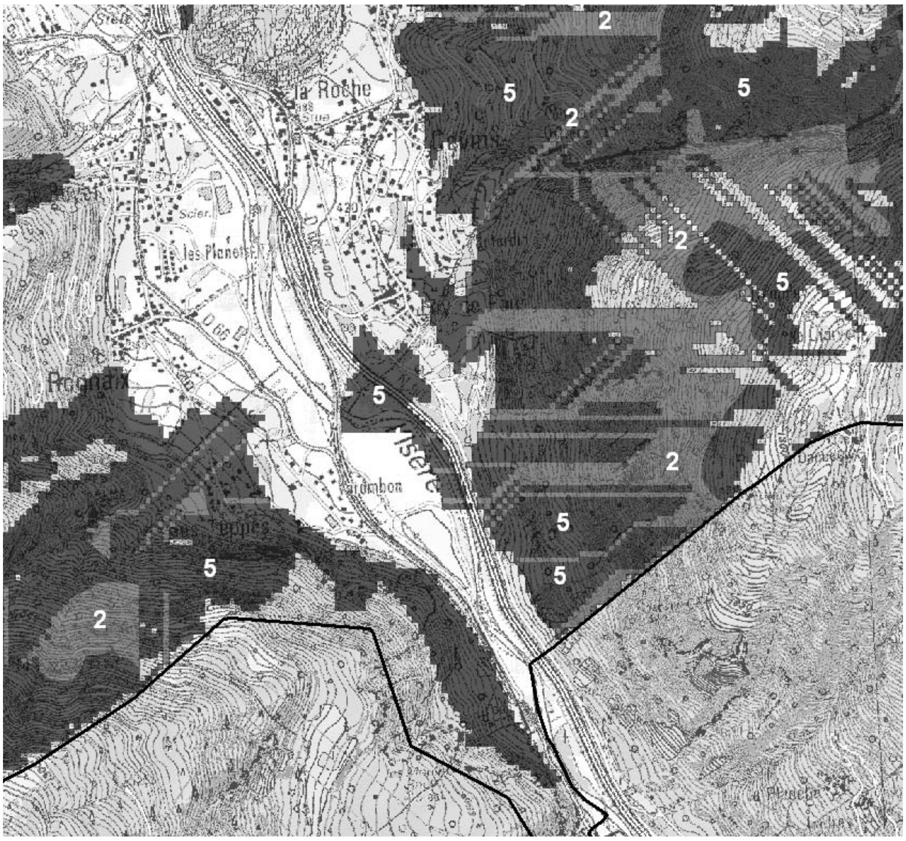

Fig. 5: Protection forests classified in ZIFP

The Fig. 5 is an example of ZIFP classification in one of the studied areas. On this area, human facilities are significant: several towns and villages (more than 10 buildings), motorway, rail road, power line. Consequently the stake quotation is 3 high. According to the photointerpretation, the forest is a dense composite stand: conifers and deciduous trees. The proportion of conifers is higher at the top of the forest, and about 0 % at the footslope. It is considered as stable for the next 30 years, so the priority level is medium, according to Table 3. The hazard mastership index is 5 for rockfalls: start points are all in the stand, the density is higher than 250 trees / ha, and the basal area is higher than 25 m² / ha (see Table 2). For avalanches, the index is 5 when conifers are correctly represented (top of hillside), and 2 when the stand is composed of deciduous trees. According to Table 4, this protection forest has a ZIFP of 2 and 5. Compartments with a ZIFP of 5 have a good role of protection. Forest actions will be needed in the other compartments, as defined in the *Guide de Sylviculture de Montagne* (Cemagref *et al.*, 2006).

CONCLUSION

The GIS model for the protection forests zoning is composed of four steps. The first and the most important one is the simulation of the maximal runout envelop of rockfalls and avalanches, based on the Energy line principle. Then, the determination of forests concerned by hazards and the hazard mastership index, from a GIS crossing between hazards and forests, is also an important part of the model and depends on the precision of the stand analysis. Stake analysis is made in the third step. Finally, protection forests, classified by prioritized zones for forest interventions, are mapped, according to the hazard mastership index and to the priority levels, defined by the stake analysis. The Interreg project IFP started in 2008 and will end in 2011. At this date, there will be a map of all protection forests in 4 studied areas in France: Grenoble metropolis (Isère), Haut Chablais and Chamonix valley (Haute Savoie) and Arlysere (Savoie), for a total area of 2200 km². The GIS method will be validated by these studied areas and could be applied anywhere to have an exhaustive idea of the distribution and the proportion of protection forests. Furthermore, the knowledge of all protection forests will allow to adopt a specific silviculture, defined in 2006 by a European Project called “Sustainable management of mountain forests”, to maintain or increase the protective role of our mountain forests.

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