Multifunctional management of mountain forests Compromises between the protection and conservation functions

How can the balance between protection against natural hazards and biodiversity conservation be determined at each stage in forest development? This study provides a number of answers in view of improving multifunctional management.

Mountain forests are today recognised for their multifunctionality and in particular for biodiversity conservation and protection against natural hazards.

They are, for the most part in France, relatively recent forests that colonised cultivated and grazing zones that were abandoned during the 1800s and 1900s. Consequently, they are now engaged in a process of secondary succession that has not yet stabilised. Forest stands that are today considered mature are very often even-aged stands largely dominated by the first cohort made up of large or very large trees. A progressive transition to a less regular (less even-aged) structure is underway in the oldest stands.

The purpose of this article is to present the changes in stand structure (see box ①) from beginning to end of secondary succession in a context of natural dynamics or "cautious" management and to discuss the impacts of the structural changes on the two functions (biodiversity protection and protection against natural hazards), in view of answering two questions.

- In the course of succession, are there structures that optimise the two functions?
- In the course of succession, are there structures that preclude one or the other of the two functions?

① STRUCTURE OF FOREST STANDS

Generally speaking, the structure of a forest stand comprises:

- the tree-species composition,
- the size distribution of living and dead trees (diameters, heights),
- the spatial pattern of trees on the site (e.g. clumping).

In this initial handling of the topic and given the available data, we deliberately limited this study to the dendrometric structures of living trees (density, basal area, diametric distributions). Similarly, the protection function is limited to rockfalls, the main natural hazard in mountain regions in terms of both the number of events and the surface areas affected.

In this document, we often refer to tree sizes, based on the diameter measured at 1.3 metres from the foot of the tree ($d_{1.30}$), that are very commonly used in mountain forests.

- Small (S) : $10\text{ cm} \le d_{1.30} < 27.5\text{ cm}$;
- Medium (M) : $27.5\text{ cm} \le d_{1.30} < 42.5\text{ cm}$;
- Large (L) : $42.5\text{ cm} \le d_{1.30} < 62.5\text{ cm}$;
- Very large (VL) : $d_{1.30} > 62.5\text{ cm}$.

Dynamic stages with clearly differentiated dendrometric structures

There is general agreement to distinguish six main stages in the natural dynamics of mountain forests (*Guide des sylvicultures de montagne* ; Gauquelin et Courbaud, 2006; figure ❶).

The first three stages (initial, self-thinning and ageing) occur sequentially over time. The ageing stage, during which the stand continues to mature (steady growth of dominant trees, very low mortality), currently represents a large percentage of surface areas in France and is often very long (several decades to centuries).

Starting with the ageing stage, given the size of the trees, the forest is considered mature.

The three subsequent stages (collapse, irregular, renewal) often take place in parallel and researchers have noted the difficulty in determining their relative weights. Many dendrochronological studies (see, for example, Brang *et al.*, 2006, for a summary) have shown that, in the Alps, the irregular and renewal stages are much more frequent and widespread than the collapse stage.

This "natural" succession sequence has, to date, not been significantly modified by forest management, which remained very "cautious" during the 1900s. In forests intended for protection against natural hazards, forest managers worried that sylvicultural intervention could destabilise stands and hinder the protection function. What is more, toward the end of the 1950s, logging in mountain regions became less and less profitable and very extensive management techniques spread to stands without any clear protection function, but that were very difficult to work (relief, access).

To study changes in forest structure during the succession, we selected 22 plots from a network of permanent plots set up by ONF (French National forestry agency) and Cemagref in the Northern Alps, then regrouped the 22 into five groups according to their diametric structures (see figure ❷).

Three groups have unimodal diametric structures.

- Group 1 (GR1) comprises four plots with essentially small trees (d_{av} = 19.3 cm). It is representative of young stands, at the end of the initial stage.
- Group 2 (GR2) comprises four plots with essentially medium-sized trees (d_{av} = 32.7 cm). It is representative of slightly older stands, at the end of the self-thinning stage (see photo ❶) ;
- Group 3 (GR3) comprises four plots with a majority of large and very large trees (d_{av} = 42.2 cm). It is representative of old, even-aged, regular stands dominated by the initial cohort (see photo ❷).

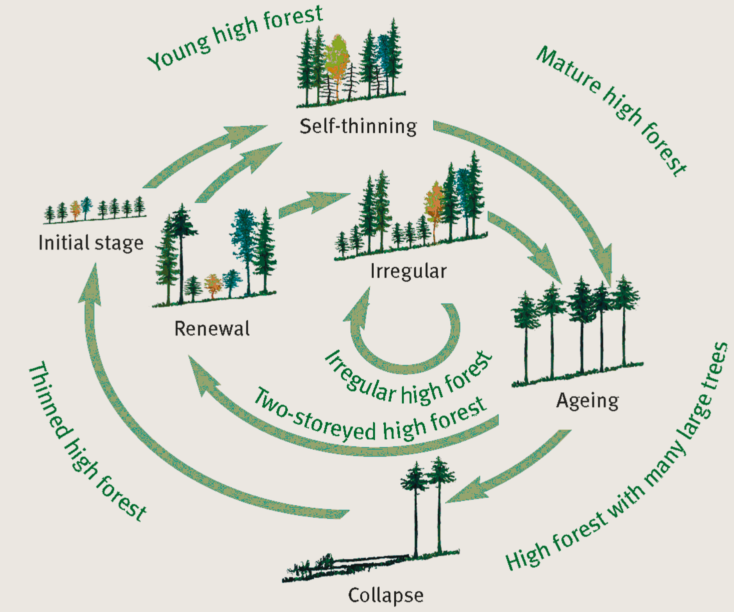
The two other groups have more diversified diametric structures.

- Group 4 (GR4) has a bimodal diametric structure. Large and very large trees (the initial cohort) are still numerous, as are small trees (the new cohort). Consequently, the average diameter is fairly high (d_{av} = 35.0 cm), but lower than in GR3. GR4 is more or less representative of the renewal stage (see photo ❸) ;
- Groupe 5 (GR5) has a diametric distribution corresponding to the irregular stage (constant drop in numbers from S to L&VL). The average diameter is fairly small (d_{av} = 24.5 cm).

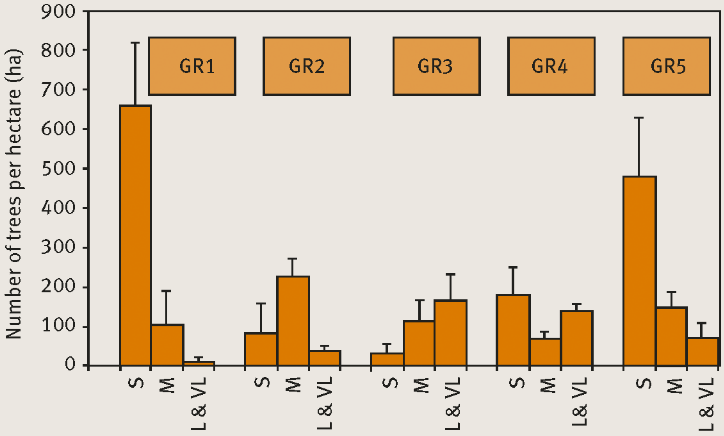
Total densities (see table ❶) are very high at the end of the initial stage (GR1 = 774 stems per hectare). Densities drop significantly during self-thinning (GR2 = 352 stems per ha), then more slowly during the ageing stage (GR3 = 31 stems per ha). They then increase slightly during renewal (GR4 = 388 stems per ha) and return to high levels during the irregular stage (GR5 = 694 stems per ha).

Total basal areas (see table ❶) progress inversely from the end of the initial stage (GR1 = 26.2 square metres/hectare) to the ageing stage when they reach high values (GR3 = 49 m^2/ha). They remain high during the renewal (GR4 = 49 m^2/ha) and irregular (GR5 = 44 m^2/ha) stages.

❶ **Natural dynamics of mountain forests (Gauquelin et Courbaud, 2006)**



❷ **Diametric structures of the plot groups**



❶ **Plot at end of self-thinning stage, with essentially medium-sized trees (GR2).**

❷ Plot during ageing stage, with a majority of large and very large trees (GR3).

❸ Plot during renewal stage, with large numbers of both small and large/very large trees (GR4). N.B. Notice the large dead trees still standing.

Implications for the biodiversity-conservation function

Biodiversity indicators may be divided into two categories (Lindermayer *et al.*, 2000).

- Direct indicators based on the presence of key or indicator species, that signal a high degree of biodiversity. Use of these indicators requires some caution because the relation between the presence of an indicator species in a stand and the overall biodiversity of the stand is rarely clear.

- Indirect indicators based on the stand structure. The greater the heterogeneity or complexity of the stand structure, the greater the variety of ecological niches offered and the more the stand is likely to receive a high number of animal and plant species, however, here again, the relation must be consolidated. These indicators are often preferred because they can be modified by managers.

Diametric structures are very often used to assess stand heterogeneity. Taking into account the data available from the plots, we calculated two indicators that reveal heterogeneity of tree diameters.

- The Shannon index (see box ❷) for the distribution of the basal area according to the tree-diameter classes defined above (Shannon_D).

- The cumulative basal area of L and VL trees because larger trees are often home to specialised biotic communities (of proven value for biodiversity).

❶ Dendrometric characteristics of plots.

Group	Plot	Type of stand	Total density	Total basal area	Average diameter
1	GR1_1	Beech, spruce, fir	672	26.2	19.9
	GR1_2	Beech, diverse hardwood	908	20.2	16.3
	GR1_3	Spruce, fir	688	19.2	17.7
	GR1_4	Fir	828	39.3	23.4
	Average (stand. deviation)		**774 (114)**	**26.2 (9.2)**	**19.3 (3.1)**
2	GR1_1	Spruce,	280	29.0	35.1
	GR1_2	Spruce,	304	25.1	31.2
	GR1_3	Spruce,	468	34.6	29.1
	GR1_4	Beech	355	36.3	35.4
	Average (stand. deviation)		**352 (84)**	**31.3 (5.2)**	**32.7 (3.1)**
3	GR1_1	Fir, spruce,	364	71.4	48.9
	GR1_2	Spruce,	214	33.4	41.7
	GR1_3	Spruce,	386	52.2	40.2
	GR1_4	Spruce	280	38.1	38.1
	Average (stand. deviation)		**311 (79)**	**48.8 (17.1)**	**42.2 (4..7)**
4	GR1_1	Fir, spruce, beech	380	42.4	32.4
	GR1_2	Fir, spruce, beech	320	42.3	36.9
	GR1_3	Spruce, fir	272	44.5	39.8
	GR1_4	Fir, spruce	496	47.8	30.2
		Spruce, fir	472	68.4	35.6
	Average (stand. deviation)		**388 (96)**	**49.1 (11.0)**	**35.0 (3.8)**
5	GR1_1	Fir, diverse hardwood, beech	956	59.9	24.8
	GR1_2	Spruce	812	67.3	26.7
	GR1_3	Spruce	496	27.8	23.6
	GR1_4	Beech, diverse hardwood	729	36.8	21.7
		Beech, fir, diverse hardwood	477	29.0	25.7
	Average (stand. deviation)		**694 (206)**	**44.2 (18.3)**	**24.5 (1.9)**

❷ Calculation of the Shannon Index

For a variable V divided into i classes, the equation is shown below.

$$Ish = -\Sigma_i [p_i \times \ln(p_i)]$$

where p_i is the relative weight of variable V for class i (V_i/V_{tot}).

We added to these two indicators a third that indicates the heterogeneity of heights, i.e. a Shannon index for the distribution of the basal area according to tree strata (Shannon_str).

The Shannon_D index (see figure ❸) shows the differentiated diametric structures of the five groups. The three groups with unimodal structures are less heterogeneous than GR4 (bimodal structure) and GR5 (constant drop in numbers from S to L&VL).

Though GR4 and GR5 do not stand out using the Shannon_D index, they clearly stand out in terms of the basal area of L and VL trees (see figure ❹), which is much higher for GR4. GR3 also has a much higher basal area of L and VL trees.

The Shannon_str index (see figure ❺) is very difficult to interpret because there are significant variations in groups. Strata are a difficult parameter to determine in the field. However, it would appear that GR4 and GR5 have much more heterogeneous height distributions than the other three groups.

On the basis of the three indicators, the three stages ageing, renewal and irregular are those most likely to show high biodiversity levels, due to the numbers of VL trees (ageing and renewal stages) or due to the diversity of sizes (renewal and irregular stages). The renewal stage is the most heterogeneous.

Implications pour la fonction de protection contre les risques naturels (cas des chutes de pierre)

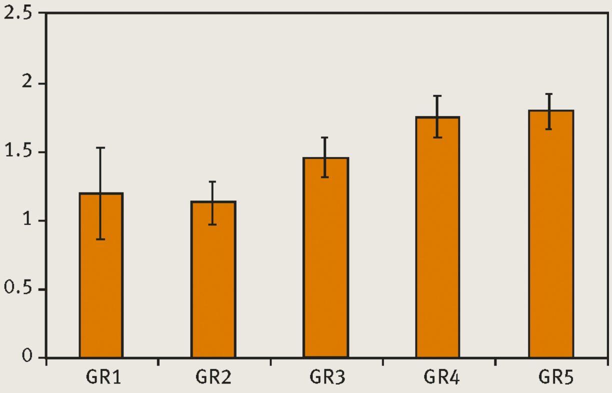
Dorren *et al*. (2005) developed a digital simulation algorithm, Rockyfor3D, to map rockfall trajectories. It is one of the first models to integrate the influence of forest vegetation on the propagation of falling rocks. It takes into account the presence of trees as potential obstacles on slopes. The approach is probabilistic.

Three parameters are set for each tree:

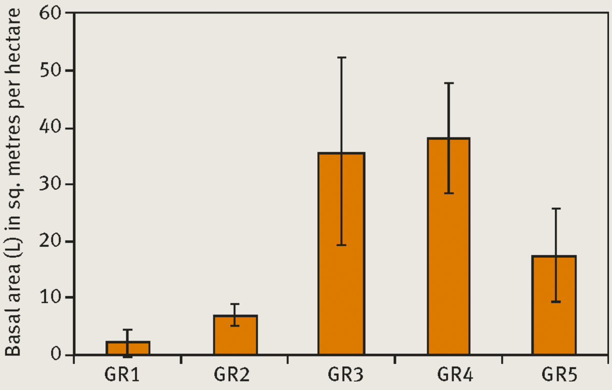
- position, either measured in the field or generated by the model on the basis of the overall stand characteristics;
- diameter, because a tree hit by a rock dissipates the energy of the rock. The level of dissipation, which corresponds to a reduction in the speed of the rock, depends on the diameter of the tree and the point of impact (scraping, lateral, frontal). The greater the diameter, the greater the dissipation.
- species, because hardwood species absorb, on average, more energy than conifers.

Using the software, we simulated the propagation of falling rocks through the 22 study plots. Precise mapping of the trees on each plot was not available, so the coordinates (x, y) of trees were generated randomly for each plot.

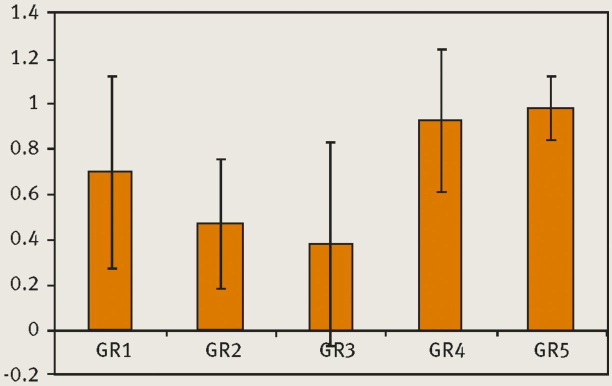
❸ Shannon_D indices.



❹ Basal area of L and VL trees.



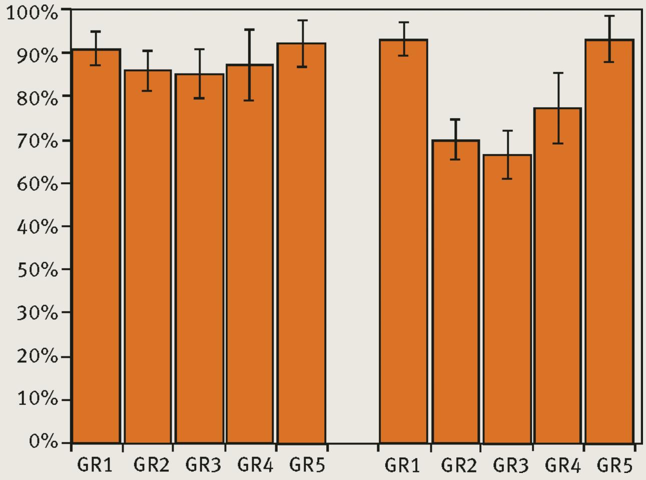
❺ Shannon_str indices.



❷ Initial conditions set for simulations of falling rocks

Site characteristics	Release characteristics
Average slope : 38° Soil : • Average normal restitution coefficient (hardness) $r_n = 0.36$ • Average tangential restitution coefficient (rugosity) $r_t = 0.77$ Vegetation : • First 40 metres without any forest vegetation. • Next 85 metres depend on the characteristics of each plot.	Single starting zone Number of rocks launched: 10 000 Height of fall: 5 metres Initial speed of rocks: zero

❻ Percentage of projectiles stopped at a distance of 125 metres from the starting point. Rocks 0.5 m³ in size on the left, boulders 1 m³ in size on the right.



To compare the results, the study plots were (virtually) set up using the topographical characteristics of the experimental site in Vaujany. The simulations were run using the initial conditions shown in table ❷ and the topographical characteristics for which the model was calibrated and validated (Dorren *et al.*, 2005).

The simulations were run using spherical granite projectiles (density = 2.8) of two sizes, i.e. rocks 0.5 cubic metres in size and boulders 1 cubic metre in size. For each structure group and each projectile size, 10 000 simulations were run and the percentage of projectiles stopped at a distance of 125 metres from the starting point was calculated.

There are significant differences in the effectiveness of the protection function of stands against the 1 m³ boulders (see figure ❻). The densest groups (GR1 and GR5) are the most effective in slowing and stopping boulders. Boulders lose little energy at each impact, but impacts are sufficiently frequent (friction effect) to slow and even stop them. On average, following an impact, a projectile recovers its maximum propagation speed if it travels a distance of 40 metres before the next impact.

Consequently, a high number of impacts and a distance of less than 40 metres between two impacts will prevent a projectile from reacquiring its maximum energy. That is the situation observed for GR1 and GR5. A contrario, for GR2, GR3 and GR4, more energy is lost at each impact, but the distance between impacts is such that the projectile reacquires energy before the next impact.

These differences between the groups are not significant for the 0.5 m³ rocks. For projectiles of this size, the friction effect (multiple small energy losses during impacts with small trees) is compensated by major energy losses caused by a single impact with a large tree.

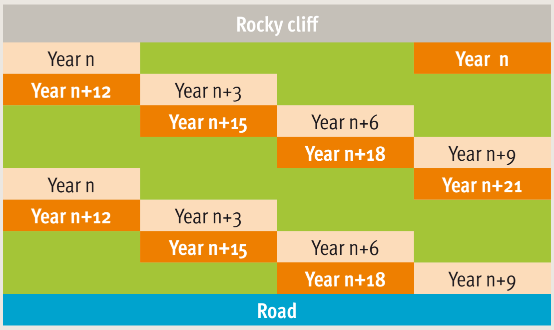
Optimising the conservation and protection functions

In light of the calculated indicators, the three stages corresponding to a mature forest (ageing, renewal, irregular) are advantageous for biodiversity. The ageing stage because of the relatively high numbers of L and VL trees in the stand, the renewal and irregular stages because of the heterogeneity in tree sizes.

Additional indicators are however required to fill out the approach. Inclusion of data on dead wood (standing and fallen) should be a means to rank the three mature stages. Throughout the ageing stage, tree mortality is very low and spread out over time. The annual mortality rate is approximately 0.5%, i.e. low amounts of dead wood may be expected. Mortality is higher during the renewal and irregular stages (annual rate between 1 and 2%). These two stages should therefore have more dead wood than the ageing stage. The data from the plots, though still incomplete, confirms this hypothesis.

The densest stages (initial and irregular) are the most effective for rockfall protection. Similar results have been obtained by Jancke *et al.* (2009) for hardwood coppice, i.e. very dense young stands (20 to 30 years) are more effective against falling rock than older, less dense stands (40 to 50 years).

❼ Diagram for plan to renew coppice over approximately 40 years.



Rocky cliff

Year n			Year n
Year n+12	Year n+3		
	Year n+15	Year n+6	
		Year n+18	Year n+9
Year n			Year n+21
Year n+12	Year n+3		
	Year n+15	Year n+6	
		Year n+18	Year n+9

Road

❹ Opening created to renew coppice in the Sonnaz (73 France) municipal forest.

The idea that the renewal stage offers less protection must be refined by taking into account dead wood. Studies have shown that a thicket of stumps, trunks and branches on the ground has a level of rugosity equivalent to or higher than that of standing trees, at least during the first ten years of decomposition.

When rockfall protection is the priority, the density effect can be put to use by precipitating stand renewal through the creation of openings that are sufficiently large (0.1 to 0.5 ha) to relaunch a process of secondary succession and by adapting the positions and timing of the openings to the characteristics of the forested slope.

This type of opening is used, for example, to renew coppice. The openings, often rectangular (20 to 30 metres wide from top to bottom and 40 metres long, are staggered (see figure ❼ and photo ❹). Similarly, in a mature forest, openings are made in older stands (see figure ❽ and photo ❺). This technique is all the more effective when the openings are positioned in pre-existing regeneration zones.

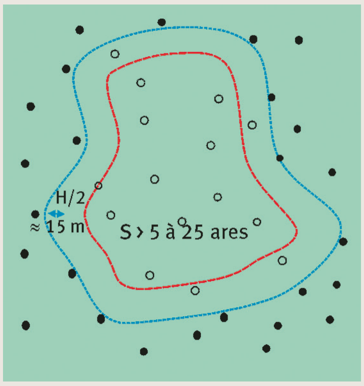
These techniques produce adjacent groups of trees in the ageing stage and in the initial or self-thinning stages. The resulting patchwork resembles the renewal stage, but with two notable differences:

- the renewal zones (openings) are larger, but their distribution over time and space is controlled;
- the stand is often renewed before the ageing stage has reached its term, i.e. before it has acquired the structural characteristics that are favourable for biodiversity conservation (VL trees, dying trees, dead wood).

In this patchwork, the later stages of the succession are under represented. It is therefore necessary to plan the creation of additional islands of ageing and senescent trees, carefully located to ensure that they do not hinder the protection function.

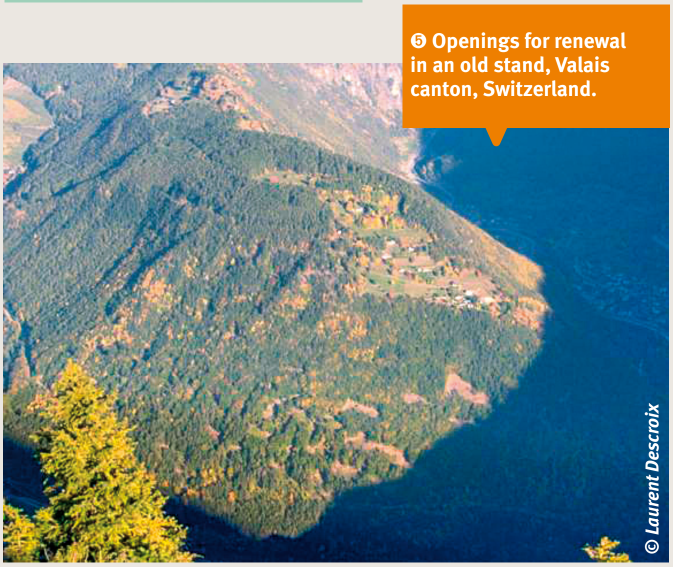
The more numerous and the smaller the openings, the closer one comes to the irregular stage which optimises the two functions of biodiversity conservation and protection against natural hazards. This stage is however difficult for forest managers to maintain for two sets of reasons.

- Ecological reasons. This technique is well suited to mixed stands of beech/fir or spruce/fir in the mountain belt, but it is not suitable for spruce stands high in the mountain belt and in the subalpine belt. At these altitudes, renewal of spruce stands requires large openings. In addition, when relief conditions are difficult, repeated minor interventions cause considerable damage to stands.
- Economic reasons. When access and operating conditions are difficult, it is worthwhile to focus work on a fewer number of interventions covering smaller areas. ■



❽ Diagram for an opening for stand renewal (source : ONF).

❺ Openings for renewal in an old stand, Valais canton, Switzerland.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