THE ROLE OF "PASSIVE" PROTECTION PLAYED BY VEGETATION AND BIOENGINEERING WORKS: AN EFFICIENT AND OPTIMAL MEAN FOR SOIL CONSERVATION

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Abstract
Vegetation and bioengineering works can play a role of "passive" protection in soil conservation, i.e. erosion occurs but sediment is retained by vegetation obstacles downslope. This paper firstly presents the state-of-the-art concerning this particular role of protection. Secondly, it gives the results of investigations carried out in marly catchments in the French Southern Alps, aimed at quantifying the efficiency of vegetation obstacles and bioengineering works for sediment trapping. The results showed that: (a) for a marly plot of less than 500 m², a downslope vegetation obstacle covering only 20% of this plot can be sufficient to trap all the sediment eroded above it, if all the vegetation is located downslope; (b) for a gully of less than one hectare, vegetation obstacles can stop sediment yield at the exit of this gully with only 33% of vegetation cover, if the vegetation is mainly located downstream of the gully; (c) bioengineering works can permit an efficient trapping of movable sediments in gully floors. Finally, this article explains how to use this improved knowledge to propose optimal solutions for soil conservation by the use of ecological engineering.

Additional Keywords: erosion, willow, Salix, ecological engineering, sedimentation, vegetation barrier

Introduction
Soil erosion is a frequent problem where erodable grounds are submitted to aggressive climate or soil use around the world (Harden 2001), especially in mountain areas (Inbar and Llerena 2000) and under Mediterranean climate (Lasanta *et al*. 2001). Erosion in mountainous catchments can often be controlled with technical engineering within torrent beds and bioengineering within small gullies, where vegetation can play a very significant role against erosion (e.g., Romero-Díaz *et al*. 1999). But nowadays in many countries, because of budgetary restrictions, the people who restore lands in mountain areas must establish optimal management for erosion control, i.e. guarantee sufficient protection against erosion with fewer interventions as possible. To do this, we think that it is not necessary to establish a total vegetation cover in a catchment to stop the sediment yield at its exit, owing to the role of vegetation obstacles in sediment trapping. This paper first presents the current knowledge and investigations on this particular role of vegetation on erosion and sedimentation, and then explains how to use this knowledge to propose optimal strategies for sedimentation control with bioengineering. Priorities and rules for bioengineering use are then proposed.

Efficacy of Vegetation Obstacles for Sediment Trapping
Current knowledge on sediment trapping processes by vegetation obstacles
Vegetation can allow to control erosion efficiently by two ways (Viles 1990): on one hand the vegetation cover can avoid erosion to occur, thus playing an "active" role against erosion, on the other hand vegetation obstacles can trap and retain sediment eroded upslope, thus playing a "passive" role of protection by sedimentation control. Many authors studied the influence of vegetation obstacles on sedimentation. Lee *et al*. (1999) showed that there could have a filtration effect of flows through vegetation. These flows deposit sediment load as a result of a reduction of their transport energy. If Dabney *et al*. (1995) showed that vegetation is more likely to trap finer sediment, other studies (Meyer *et al*. 1995) showed that vegetation obstacles could also trap coarse sediment. Deposits have then been observed upslope of vegetation barriers (Sanchez and Puigdefabregas 1994), on steeper slopes than those without vegetation (Bochet *et al*. 2000). The use of vegetation hedges on terraces for erosion control has often been tested successfully (Poudel *et al*. 1999). In particular, the vegetation hedges with Vetiver (*Vetiveria sp*.) have showed their efficiency for sediment trapping (Dalton *et al*. 1996). Kikuchi and Miura (1993) explain that the sediment accumulations due to vegetation obstacles represent stable grounds for the installation of pioneer vegetation, that moreover can only install itself on this type of substrate in degraded catchments (Guerrero-Campo and Montserrat-Marti 2000). The plants of the vegetation barriers may also develop in contact with the accumulated sediment (Sanchez and Puigdefabregas 1994), and then colonising the sediment trapped (Chappell *et al*. 1999).

Investigations on the efficacy of natural vegetation obstacles

Processes of sediment trapping can occur in the gullies of mountainous catchments, as stated by Rey *et al.* (2003a) in the French Southern Alps under a Mediterranean climate. The plants located downslope of a gully, and in particular under-shrubby and herbaceous layers located in gully floors, constitute the most efficient obstacles. An optimal dimension of vegetation obstacle has been highlighted: an obstacle only covering 20% of the downslope part of a marly zone – of surface area less than 500 m² – entirely eroded can be enough to stop the sediment yield from this zone.

These vegetation obstacles significantly reduce the sediment yield at the exit of gullies – of surface area between 500 m² and one hectare – and consequently at the exit of the whole catchment. The results of research have thus shown that the spatial distribution of vegetation in gullies is significant in reducing the sediment yield at their exit. Gullies with same total vegetation cover can then have very different sediment yields and it is possible to stop the sediment yield at the exit of a gully with a partial vegetation cover in the gully. Vegetation obstacles in right position in the gully can allow to stop the sediment yield of gullies with only 33% vegetation cover (Rey 2003), percentage a few superior but closed to the one of 20% previously cited.

Investigations on the efficacy of bioengineering works

There are various types of bioengineered structures that can be used for rehabilitation of eroded gullies. Main ones are brush layers, fascines, wattle fences and brush mats. Brush layers are made by planting the cuttings vertically in the ground or horizontally on a bench terrace. A vegetative contour hedge is then made with a large number of cuttings placed in contour lines along a slope or bank. Fascines are made of cuttings gathered into bundles, piled up behind metal, deadwood, or live stakes. Wattle fences also consist of cuttings, but these are woven individually around stakes. Brush mats involve covering the ground with a layer of cuttings. Bioengineered structures may or may not be accompanied by the planting of grass or other plants. Such planting is effective only if done on stabilised and loose earth, in other words, in the areas of alluviation uphill of the structures. As a rule, grass planting is not used very much. Although experiments with grass seeding under jute netting have shown that the method reduces erosion fairly efficiently, the cost has turned out to be prohibitively high. The morphology of bioengineered structures renders them more or less efficient for the short-term trapping of sediment. Brush layers and brush mats have aerial parts that allow them to trap the sediment going through them, somewhat like a comb. On the other hand, fascines and wattle fences may not be capable of trapping the sediment until the cuttings in them have begun to resprout, although the resistance of fascines and wattle fences does make them the best-adapted structures for revegetating gully floors. A way to combine the advantages of brush layers, brush mats and fascines is to place rows of cuttings over the aggraded material on top of the fascines in order to create vegetative hedges or covers.

Studies were thus carried out to analyse the efficacy of bioengineering works for sediment trapping and retention in torrential catchments in the Southern Alps of France, under a Mediterranean climate (Rey *et al.* 2003b). These bioengineering structures should lead to the development of vegetation barriers and covers, capable of trapping the sediment. The results have shown that, despite of a very dry climate and the presence of heavy rainfall events, brush layers on fascines, made of willow (*Salix*) cuttings, can permit an average trapping of 0.05 m^3 sediment per work in one year, and that brush layers with brush mats on fascines can permit an average trapping of 0.11 m^3 sediment per work in one year. The results have thus shown that it is possible to retain sediment with bioengineering works from the first year onwards.

Improved knowledge on the influence of vegetation on sedimentation in gullies can be used to propose optimal strategies for sedimentation control with bioengineering, for rehabilitation of eroded mountainous catchments.

Rehabilitating Eroded Ecosystems

Areas for priority action

The principle of optimal management requires the best possible spatial definition of the priorities for action, and that includes determining the areas for non-intervention.

At the scale of a region, it is possible to determine which catchments need rehabilitation first, the choice being influenced especially by socio-economic issues.

At the scale of a priority catchment, it is possible to determine which gullies need rehabilitation first. For this, there are two criteria: the erodibility of the terrain and the presence of natural vegetation. The erodibility of the terrain depends directly on physical factors such as lithology or topography. The most erodible terrain will be a priority for rehabilitation. The presence of natural vegetation can be an indication that the erosion is less active than elsewhere, and therefore that revegetation might be more successful there. To identify these gullies, it is possible to use a gully typology like the one established for marls (Figure 1) (Rey 2002). Among the "active" gullies (with significant sediment yield at their exit), rehabilitation will be a matter of priority in gullies where erosional activity is more or less curbed because plant dynamics prevail (active gullies with biostasic tends) rather than in gullies that tend to be more active because erosional dynamics prevail (active gullies with rhexistasic tends).

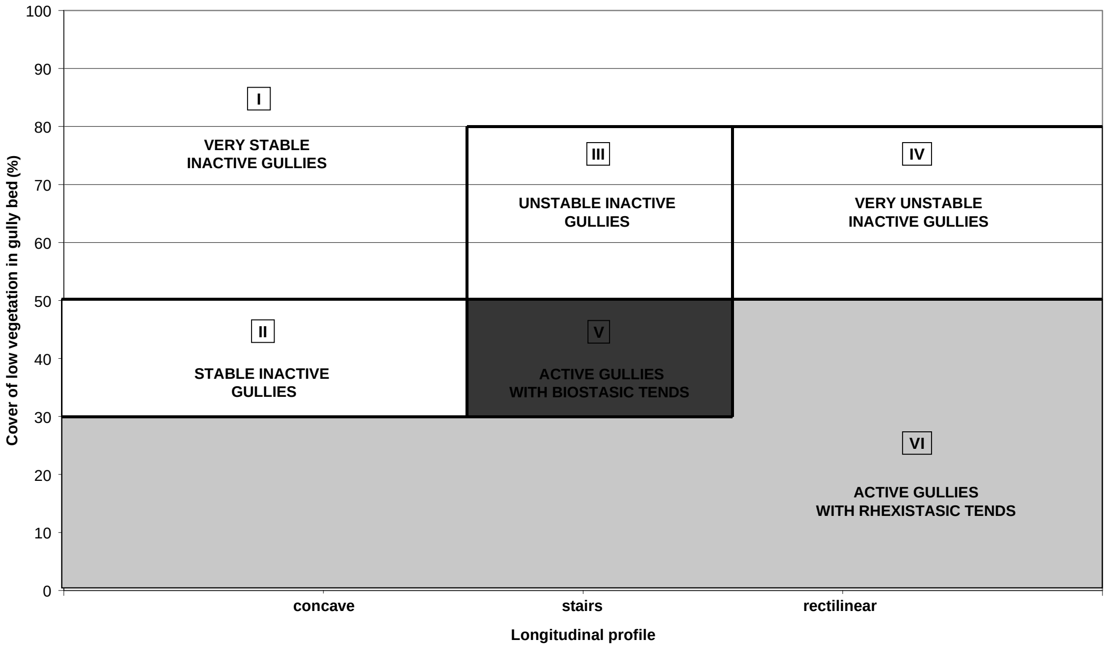

Figure 1. Priorities of rehabilitation actions among the active gullies (in bold grey: 1st priority; in light grey: 2nd priority)

Since the influence of vegetation is effective mainly at the gully scale, the gully will be the elementary scale for rehabilitation activity. Within a gully under consideration for rehabilitation, it is possible to determine the extent of correction needed to make the gully "inactive" (i.e. to stop the sediment yield at its exit). For this, one can operate on the following principle: given that vegetation on gully floors plays a more important role in erosion control than vegetation on gully slopes or interfluves, the spatial distribution of vegetation in a gully is important for reducing sediment yield at gully outlet. To reach optimal inactivity at the gully outlet, there must be a plant cover in the downhill part of the gully. We have observed that it takes a minimum plant cover rate of 33% to reach a near-zero sediment yield at the outlet, as long as the vegetation covers the bottom of the thalwegs fairly well. With an optimal localisation of vegetation obstacles, it may take a minimum plant cover rate of 20%. It seems reasonable to aim for that minimum rate on the gully floors for revegetation operations. Bioengineered revegetation operations should be carried out on gully floors first, then on the banks and, if necessary, on the lower slopes (Photo 1). So to stop sediment yield at its outlet, it is not necessary to restore the vegetation cover over an entire gully, particularly on the upper and middle slopes. If the heads are eroded and yielding sediment, the sediment will be stopped by the vegetation located in the downhill part of the gully and prevented from reaching the outlet. The heads are what we refer to as areas for non-intervention. Of course, the vegetation obstacles must be sufficiently developed over time in order to fulfil their role. To guarantee achieving the overall minimum 20% cover rate, it seems advisable to take some action on the downhill 30% of the gully, although the proportion of the area might vary as a function of the geomorphologic features of the gully. For example, if the walls are too steep, the proportion to be covered should be revised upward.

Photo 1. Optimal rehabilitation of an eroded gully with brush layers and brush mats on fascines (Photo by Freddy Rey)

Rules for rehabilitative action at the gully scale

The first step in rehabilitating a degraded catchment is to use civil engineering methods in the catchment's main streambeds. Vegetation can develop only on temporarily stabilised land so, before using vegetation to control erosion at the scale of the catchment gullies, headward erosion must be controlled by stabilising the banks of the main catchment streambeds. The first action in any rehabilitation operation, therefore, should be soil stabilisation; here, trapping sediment is the key to success. It is often thought that simply reforesting slopes can control erosion effectively. While it is true that forest cover can be very efficient in the active control of erosion, without soil stabilisation it can also be totally inefficient. Therefore, before proceeding with revegetation in the gullies, it is indispensable to build civil engineering structures in the main mountain streambeds to stabilise the base of the gullies that branch off from these main streambeds. Once a major streambed has been plugged, it is possible to consider revegetation and even making the gullies inactive. We would like to note that it is unrealistic (and even dangerous) to try to revegetate the main catchment streambeds.

Inside gullies, a strategy can be defined for choosing the appropriate bioengineered structure as a function of where in the gully to take action. Such a strategy is presented in Table 1. As we know how much sediment can be trapped by one bioengineering work in one year, it is possible to determine the number of bioengineering works to install to reduce the sediment yield at gully exits from the first year onwards. Monitoring and maintenance of the bioengineered structures are indispensable to ensure that the minimum 20% cover rate is achieved, and especially that the vegetation does indeed cover the key areas of the gully floor.

Table 1. Strategy for choosing the appropriate bioengineered structure as a function of where in the gully to take action

Position in the gully	floor	bank	slope
Structure to use	brush layers and brush mats on fascines	brush layers and brush mats	brush layers

Conclusion

Strategies of optimal bioengineering have been proposed for sedimentation control and soil conservation in mountainous catchments. These strategies can be used to solve problems of high sediment yield at the exit of catchments. For example, ecological restoration of eroded zones, aiming at retaining sediments within catchments, should make it possible to decrease the sediment yield within hydroelectric dam impoundments. Then, this solution would constitute a sustainable and economical alternative in comparison with an expensive flush of accumulated sediments in the dam impoundments.

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