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Can bioengineering structures made of willow cuttings trap sediment in eroded marly gullies in a Mediterranean mountainous climate?

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ABSTRACT

In the Southern French Alps, high sediment yields from marly catchments cause socio-economic and ecological problems downstream. Bioengineering structures made of willow cuttings could be used for efficient and sustainable sediment trapping in eroded gullies in order to decrease sediment yield at their outlets. However, little has been done to quantitatively assess the efficiency of such structures for trapping sediment or to improve their performance. The objectives of this study were to analyze the ability of bioengineering structures to enhance vegetation development and sediment trapping in marly gullies in the Southern French Alps, under a mountainous and Mediterranean climate. For five years after the restoration operations, we monitored 101 bioengineering structures using willow (*Salix*) cuttings, including 55 brush layers on wooden sills (BL) and 46 brush layers with brush mats on wooden sills (BLM), 1.2 m wide and 2 m long, installed on the floors of eight experimental marly gullies. The results showed that the ultimate survival of willow cuttings can be assessed after three years. Gully size and aspect appeared to be the most important factors influencing resprouting rates. By avoiding south-oriented gullies and those smaller than 1000 m^2, 75% survival rates per structure may be achieved. The results also showed that BL trapped 0.18 $m^3\ yr^{-1}$ of sediment per structure on average and BLM 0.21 $m^3\ yr^{-1}$, but potential maximum values may reach 0.28 and 0.40 $m^3\ yr^{-1}$ over one year on BL and BLM, respectively. Therefore, bioengineering structures made of willow cuttings can be used to trap significant quantities of sediment from the first year onwards and efficiently restore eroded marly gullies under a Mediterranean mountainous climate. It also provides design criteria to guide future restoration actions and future investigations in the Southern French Alps.

1. Introduction

Erosion control is a major challenge in many mountain ecosystems in a Mediterranean climate, such as in France (Mathys et al., 2003), Spain (Cerdà, 2002; Martínez-Casasnovas et al., 2004) and Morocco (Tribak, 1998). In the marly badlands of the Southern French Alps, torrential floods heavily loaded with eroded sediment, responsible for ecological and socio-economic issues (e.g. debris flows and silting of reservoirs; Verstraeten et al., 2006), have stressed the need for ecological restoration of degraded lands.

The importance of vegetative cover in preventing soil erosion is well known (Rey et al., 2004; Stokes et al., 2008), particularly in gullies (Descroix and Mathys, 2003; Poesen et al., 2003). At the end of the 19th century, massive afforestation operations have been carried out in marly catchments in the South of France to increase vegetation cover (Vallauri et al., 2002), and locally resulted in marked reduction of erosion rates. In some restored areas, erosion rates are now less than 3 $m^3\ ha^{-1}\ yr^{-1}$ compared to 100 $m^3\ ha^{-1}\ yr^{-1}$ in a similar eroded area devoid of vegetation (Mathys et al., 2003).

The effects of vegetation on erosion processes are manifest and have been repeatedly reviewed in the past (e.g. Greenway, 1987; Styczen and Morgan, 1995; Gyssels et al., 2005). They can be divided into active protection, including hydrological effects (Wei et al., 2009; Podwojewski et al., 2011; Preti et al., 2011), mechanical effects (De Baets et al., 2007; Hudek et al., 2010; Phillips et al., 2011), and passive protection, which corresponds to sediment retention by the aerial parts of plants before it reaches the main rivers (Bochet et al., 2000; Descheemaeker et al., 2006; Burylo et al., 2012a). Several studies have indeed highlighted the ability of vegetation barriers to favor sedimentation (Nyssen et al., 2000; Rey, 2005). These obstacles can act as filters capable of trapping sediment transported by runoff (Dabney et al., 1995; Abu-Zreig, 2001). Bochet et al. (2000) observed that the morphology of the vegetation obstacle is a significant factor, i.e. that it should cross the whole profile of the gully floor and that plant species play significant roles in sediment trapping. Several authors have shown that the length of vegetation coverage, parallel to the concentrated runoff, has significant effects on sediment trapping (Van-Dijk et al., 1996; Lee et al., 1999; Abu-Zreig et al., 2004).

During the past 10 years, several studies have highlighted the importance of vegetation distribution in erosion and sedimentation control, as a consequence of sediment trapping processes. Rey (2003) showed that gullies with similar vegetation cover but different spatial

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distribution could have different erosion rates. Molina et al. (2009) showed that the presence of a dense vegetation cover in gully floors can result in lower erosion rates, and that 0.035 m^3 of sediment were deposited upstream of vegetation barriers each year and each meter of gully floors. Rey (2004) observed that a vegetation cover of only 20% is enough to trap sediment from eroded areas and stop the sediment yield from 500 m^2 gullies, given that vegetation is mainly distributed on the downslope part of the gully floor and composed of grass and low shrubs. However, sustainable development of vegetation in these degraded lands remains difficult and sometimes unpredictable due to severe climatic conditions, poor soil fertility and active erosion along the gully floors (Reubens et al., 2009; Wang et al., 2011). Therefore, recent restoration strategies focus on punctual actions, with bioengineering structures, acting as vegetation barriers, installed in gully floors, with potential impact on sedimentation on the catchment scale (Rey, 2005, 2009).

In the Southern French Alps, many bioengineering techniques rely on the use of willow (*Salix* sp.) cuttings, which are mainly planted to build fascines, brush layers and brush mats (Gray and Sotir, 1996). The genus *Salix* is widely used for environmental applications worldwide, including land rehabilitation, phytoremediation or agroforestry (Evette et al., 2009, 2011; Kuzovkina and Volk, 2009). In mountainous climates, many successful uses of willow cuttings have been reported, such as in the Central European Alps (Florineth, 2000; Moser and Stangl, 2000), the Rockies in North America (Polster, 1997; Sotir, 1999) and Nepal (Sharma, 1999; Lammeranner et al., 2005). Its ecological characteristics, including rapid growth rate, resprouting ability and tolerance to drought, heat and frost, may make it particularly suitable for ecological restoration in harsh environments, such as the marly badlands of the Southern French Alps (Rey, 2009). In addition, *Salix* sp. are used for erosion control due to high shoot density and good rooting ability, which are characteristics strongly influencing sediment retention (Burylo et al., 2012a) and soil fixation (Burylo et al., 2011, 2012b), respectively.

The use of bioengineering structures made of willow cuttings may thus provide an interesting approach to promote sediment retention and reduce sediment yield from gully systems. They could be a cost-effective method since the whole gully system does not need to be restored. In addition, rapid outcomes can be expected, i.e. a reduction of sediment yields during the first years after restoration. However, little is known about the efficiency of bioengineering structures made of willow cuttings for sediment trapping in marly gullies in a Mediterranean mountainous climate. In particular, very little quantitative data are available on the survival of cuttings in such a severe climate or on the amount of sediment trapped. We also need to gather more data on factors influencing the survival of cuttings as well as on the influence of their survival on sediment retention, to deepen our understanding of restored gully systems and provide a sound scientific basis to improve future ecological restoration projects.

The objective of this study was to fill this gap by firstly investigating the survival of willow cuttings in a Mediterranean mountainous climate and the factors influencing it; secondly monitoring sediment deposition upslope of the vegetation barriers resulting from these cuttings. One hundred and one bioengineering structures, divided into eight experimental gullies, have been studied since 2002 and for five years after gully restoration. Analyses were first performed to assess cutting survival and the effect of gully aspect and size on it, with an assumption that both parameters influence the quantity of available water and thus survival of the cuttings. We then compared the efficiency of dead bioengineering structures – i.e., where no cuttings regenerated – versus live structures for sediment trapping.

2. Materials and methods

2.1. Study site

The Saignon catchment (Southern French Alps, 44°20′N, 6°1′E), a 400 ha gully catchment, was selected as the experimental site (Fig. 1). The geology mainly consists of Jurassic black marls (Callovian and Bathonian) (Oostwoud Wijdenes and Ergenzinger, 1998). Two hundred years ago, weathering of this very erodible land led to permanent bare gullies with flow all year around (Vallauri et al., 2002) (Fig. 2). The bedrock is weathered by freeze–thaw processes. Eroded materials are transported from the gully slope to the gully floor by gravity and surface runoff. Concentrated runoff then transports materials to the gully exit during heavy rainfall events. In an experimental gully occupying 1300 m^2, Mathys et al. (2003) explain that bedload sediment represents around 15% of the total sediment. On the scale of a 1 km^2 catchment, this rate is around 40%, due to weathering of the marly material during its transport. Erosion on marly gully slopes devoid of vegetation is around 1 cm yr^{-1} and sediment yield is 100 m^3 ha^{-1} yr^{-1} on this type of lithology in the Southern French Alps (Mathys et al., 2003).

Part of the study site was first restored at the end of the 19th century, mainly with Austrian black pine (*Pinus nigra* Arn. subsp. *nigra*) plantations. Where ecological restoration was effective, vegetation communities have spread and diversified. Vegetation cover is mainly composed of Austrian black pine and common pine (*Pinus sylvestris*) for the trees, whitebeam (*Sorbus aria*), opalus maple (*Acer opalus*) and restharrow (*Ononis fruticosa*) for the shrubby layer, and calamagrostide (*Achnatherum calamagrostis*) for the herbaceous layer. Soils, described as regosoils, are still poorly structured, but bio-structuring and biological activities are now significant, with large earthworm communities (Vallauri, 1999). Top layers are made of coarse marl fragments within a fine silty matrix and present low carbonate content, from 20% to 35% with pH varying from 7.8 to 8.1 (Oostwoud Wijdenes and Ergenzinger, 1998).

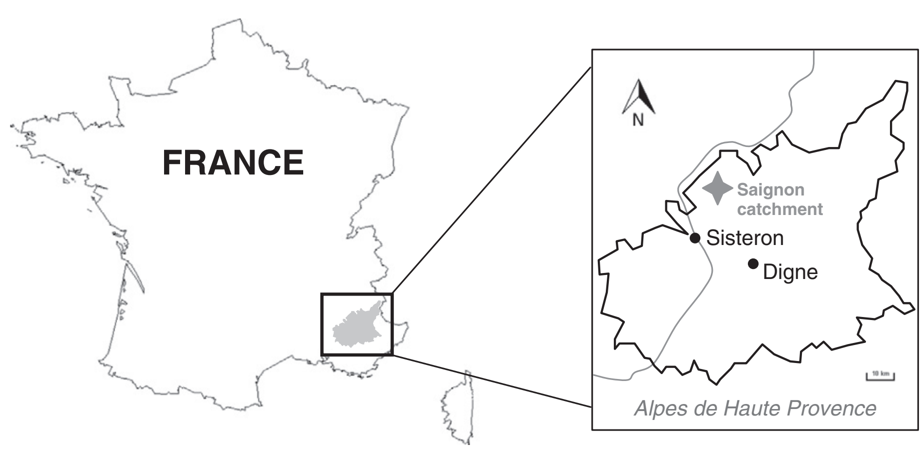

Fig. 1. Map of the experimental site (Saignon catchment).