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Vegetation dynamics on sediment deposits upstream of bioengineering works in mountainous marly gullies in a Mediterranean climate (Southern Alps, France)

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Abstract

Current erosion-control studies in mountainous catchments emphasize the effectiveness of bioengineering works in constructing vegetation barriers that are designed to trap and permanently retain sediment upstream of such barriers. Plant establishment and succession should result in colonisation of these sediment deposits, thereby improving the trapping capacity of the works. The aim of this study is to evaluate the ability of the natural vegetation to colonise and grow on sediment accumulated upstream of 29 bioengineering works. They were constructed on the channel bottom of two marly gullies in the mountainous Southern French Alps region, which has a Mediterranean climate. We analysed the soil seed bank in sediment deposits after a germination experiment conducted in the laboratory, where soil cores were placed in a non-limited water condition. We also determined the standing vegetation which developed on the sediment deposits on field sites over 2 years of drought (2003 and 2004). The results show that the number of plants was $80/m^2$ on average in the samples studied in the laboratory, vs. $31/m^2$ in 2003 and $20/m^2$ in 2004 on the field sites, with a total diversity of 40 species. Therefore, despite 2 years of drought, natural plant colonisation occurred on the sediment deposits. An improvement in soil water conditions slightly increases the capacity of the sediment deposits to allow seed germination. However, despite the initial success in vegetation colonisation, plant abundance and recovery were rather low, which suggests that vegetation established itself very slowly.

Introduction

Erosion is one of the major problems affecting ecosystem structure and functioning. According to several authors, marly soils, particularly black marls, are one of the most erodible substrates, in particular in the Mediterranean climate (Descroix and Mathys, 2003). A recent study conducted in the Southern French Alps in a badland area devoid of vegetation has shown an erosion rate over $100\ m^3\ ha^{-1}\ year^{-1}$ in marly catchments (Mathys et al., 2003). In gullies, eroded sediment is transported and deposited on the gully floors (Oostwoud Wijdenes and Ergenzinger, 1998). Then it is removed to the gully outlet by concentrated runoff during heavy rainfall events, avoiding soil from developing in eroded gullies.

The vegetation cover can prevent marly soil erosion and trap some of the sediment eroded within a catchment (Bochet et al., 2000; Rey et al., 2004), but erosive conditions in gullies restrict natural colonisation and establishment of vegetation (Cohen and Rey, 2005). However, installing vegetation on eroded lands is possible using afforestation (Toro and Gessel, 1999) and

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soil bioengineering works (Morgan and Rickson, 1995) which can be made of willow (*Salix*) cuttings (Gray and Sotir, 1996). In gullies, the most effective way to reduce or halt erosion has been to stabilise the gully floor, then revegetate the gully walls to avoid surface erosion (Yadav and Bhushan, 2002). Successful experiments have been reported from different countries, especially in Europe (e.g., Florineth, 2000; Ternan et al., 1996; Vallauri et al., 2002) and North America (e.g., Li and Eddleman, 2002; Meyer et al., 1997; Pezeshki et al., 2005). In marly gullies, bioengineering works made with brush layers on fascines can be used for gully stabilisation and revegetation (Rey, 2005). These structures can provide vegetative hedges that trap and retain marly sediment going through them, thus creating sediment deposits (or mounds) immediately upslope (Martinez-Turanzas et al., 1997).

These mounds above the brush layers constitute stable ground where the natural vegetation can develop, thus initiating the dissemination of new plant species (Guerrero-Campo and Montserrat-Marti, 2000). Development and recovery of natural vegetation may depend on many factors that can limit recruitment in the plant population. For Eriksson and Ehrlèn (1992), the lack of seed availability and the shortage of microsites are major explanatory factors. Chambers (2000) explains that seeds can be removed and lost by water flow at the soil surface. For Cerdà and Garcia-Fayos (2002), insufficient seed germination and seedling survival seem to be key factors, especially in the Mediterranean climate, which is particularly dry and warm.

If the vegetation cover naturally increases on the sediment deposits created by the bioengineering works, it may subsequently retain more eroded sediment, resulting in the structures trapping even more sediment over time (Bochet et al., 2000). The dynamics involved in this process and the inhibiting factors therefore warranted investigation, in the particular context of mountainous marly gullies in a Mediterranean climate.

The aim of this study is to evaluate the ability of the natural vegetation to colonise and grow on sediment accumulated upstream of bioengineering works, despite the unfavourable climatic and edaphic conditions. We hypothesise that bioengineering works may trap seeds, creating a seed bank, and that soil conditions, especially water availability, govern germination, seedling survival and plant growth. In this study, the relevancy of these hypotheses was tested on 29 bioengineering works built in spring 2002, which had trapped sediment by autumn 2002. We analysed the soil seed bank in sediment deposits after a germination experiment conducted in the laboratory, where soil cores were placed in a non-limited water condition. We also determined flora composition and vegetation dynamics of the vegetation that established on the sediment deposits over 2 years. It was then possible to compare the germinated seed bank of a non-restricted water soil sample and the standing vegetation, in order to determine whether bioengineering works sufficiently improve edaphic water conditions to allow germination.

Materials and methods

Study site and experimental gullies

The observations were carried out over 2 years (2003 and the first 9 months of 2004) in the Saignon catchment, a 400-ha gully catchment on marls (Southern French Alps). Experimental sites are situated in two gullies (gully 1 and gully 2) located on partly eroded black marls. Gully 1 and gully 2 cover 3830 m^2 and 2500 m^2, respectively. Altitude varies from 800 to 905 m. The general exposure of both gullies is to the southwest. Average gully wall slopes range from 100 to 120% and the average gully floor slopes from 35 to 38%. Vegetation cover is 72% in gully 1 and 66% in gully 2. The tree layer is mainly composed of Austrian black pine (*Pinus nigra* Arn. *subsp. Nigra*) and common pine (*Pinus sylvestris*). Whitebeam (*Sorbus aria*), opalus maple (*Acer opalus*) and restharrow (*Ononis fruticosa*) are the principal species of the shrubby layer, and *Achnatherum calamagrostis* dominates the grass layer. Under vegetation, soils are regosoils with mainly fine silt (Vallauri et al., 2002). All the layers are carbonated (with pH varying from 7.8 to 8.1) and poorly structured. However, biostructuring and biological activities are significant, with large earthworm communities.

The climate is mountainous and Mediterranean (Vallauri, 1999). The total average precipitation is 787 mm yr^{-1}. Rainfalls mainly occur within a few months in autumn and spring, with heavy rainfall events in autumn. The average annual temperature is 10.2 °C. The average maximum temperature of the warmest month is 28.3 °C, whereas the average minimum temperature of the coldest month is −4.2 °C. During the observation period of this study, a recording rain gauge was used to measure total rainfall and event characteristics, and a thermometer measured the daily average, minimum and maximum temperatures.

The sediment deposits

We monitored the behaviour of 29 sediment deposits upstream of bioengineering works (BW) made of willow (*Salix*) cuttings, which were brush layers on fascines installed in spring 2002 on the floors of the two experimental marly gullies (Figure. 1). Fascines are made of cuttings gathered into bundles and piled up behind stakes. They are installed in gully floors and aid in decreasing erosive and hydrological forces during heavy showers, thus permitting vegetation to develop. Brush layers are installed as rows of cuttings over the aggraded material on top of the fascines. These particular structures were selected for gully restoration because of their proven effectiveness in sediment trapping (Rey, 2005). Thirteen works were built in gully 1 and 16 in gully 2. A set of works was built in each gully, with a single one every 2 m starting from the gully outlet. They were installed along the entire length of gully floors with a slope less than 40%, thus determining the number installed in each gully. They were numbered starting from the gully outlet (for example, BW1 is the first bioengineering work starting from the outlet of the gully). All of them were 1.2 m in width and crossed the entire gully floor. In

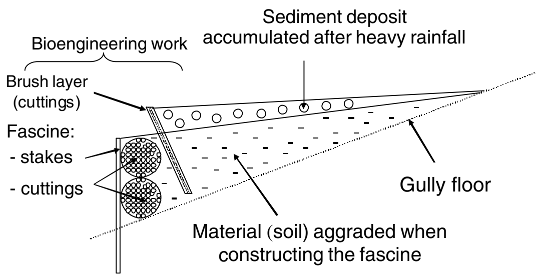

Figure 1. Longitudinal view of a brush layer on a fascine with sediment deposit upstream.

autumn 2002, heavy rainfall events had led to sediment deposits upstream of the brush layers, an average trapping of 0.06 m^3 sediment per work. The area of each sediment deposit ranged from 1.19 m^2 to 3.2 m^2. As sediment yield at the exit of an eroded gully without bioengineering structures or vegetation is theoretically approximately 100 m^3 ha^{-1} $year^{-1}$ (Mathys et al., 2003), we deduced that a single work trapped 0.06% of this theoretical yield. For all analyses, we divided the longitudinal profiles of the gullies into sectors 10 m in length. For each sector, bioengineering works were grouped. Therefore we determined four groups for gully 1 (BW1–3, 4–6, 7–9, 10–13) and five groups for gully 2 (BW1–4, 5–7, 8–10, 11–13, 14–16).

Measurement and monitoring

Soil seed bank analysis

At the end of the growing season and after the seed release (early spring of year 2004), soil samples were collected using a trowel to cut out and remove 25 × 25-cm blocks of soil. The 25-cm depth was enough to get seeds of the persistent species present in the lower and upper soil layers and to collect transient species only present in the surface soil (Thompson, 1993). Three replicates by group of bioengineering works were collected in the centre of the mounds. This bulked sample procedure was adopted because it is appropriate to avoid standing vegetation damage and side effects due to the small width of certain structures.

A seedling emergence method (Roberts, 1981) was used with these soil samples. This method is simple and appropriate for mid- to large-scale seed bank studies (Gross, 1990). Soil samples were put into cool dry storage, and afterwards stored at 0 °C for 4 months. This pre-treatment can break seed dormancy for most of perennial species. Each soil sample was mixed with an equal volume of sterilised potting compost. This mixture was then spread in four, 3-cm-thick subsample trails in a greenhouse. Because of different germination requirements, trails were kept under two sets of conditions for 3 months (1.5 months each). In this climate and this type of soil, the maximum seedling emergence occurred from late March to late May (Guàrdia et al., 2000). Early-growing species and annuals that were expected to be found in more mesic soil samples require wet soil as well as mild and fluctuating temperatures in order to germinate. The temperature of the growth chamber was 22 °C for 10 h of daylight, then 6 °C for 14 h of night, corresponding to the first period of the experiment and to the mean monthly temperatures of the study site. Usually, the species that were expected to be found in sandy soil require hot conditions to germinate (Bakker, 1989). Temperatures were maintained at 25 °C for 14 h of daylight and 13 °C for the night. To avoid marly-compost mixture dryness, relative air moisture was kept at 75–80%. After 1 month, the position of all samples was reversed in order to limit edge and microclimate effects in the growth chamber. The mixture was also lightly ploughed three times to optimise the seed–light–atmosphere interface and consequently ensure a high germination rate (Grime et al., 1988). Seedlings were counted and identified as much as possible (family, genera, species or morph level).

Standing vegetation parameters and dynamics

Adult plants and seedlings were identified and counted on each sediment deposit in spring 2003 and spring 2004, which correspond to the first 2 years of natural colonisation on the mounds. For this study, we retained two vegetation structure indices: plant abundance and species richness, i.e. the number of species. To allow comparisons, plant abundance was expressed in square metres. To study vegetation dynamics, a comparison between years was made based on plant abundance and species richness using non-parametric Wilcoxon tests. The percentage similarity in standing vegetation based on species presence/absence between years was calculated. Therefore, by comparing the results between the standing vegetation and the soil seed bank, we were able to determine the effects of the germination treatment on plant abundance, using a one-way ANOVA.

Results

Meteorological conditions during the observation period

In 2003, total precipitation reached only 586 mm, with 64 mm from 1 May to 31 July (3 months). Heavy rainfall events were rare. The heaviest intensity in 1 h was 24 mm h^{-1}. The average annual temperature was 10.9 °C. Average maximum temperatures per month were 28.8 °C in June, 29.9 °C in July and 31.4 °C in August, which was the warmest month of the year. From 1 June to 31 August, the temperatures measured were the warmest ever recorded for approximately 150 years (André et al., 2004), with 53 days when the maximum temperature exceeded 30 °C. The total precipitation during the first 9 months of 2004 was only 338 mm, with 15 mm from 1 June to 31 July (2 months). Thus precipitations were particularly low, especially during the beginning of the summer. Few and low rainfall events occurred, the heaviest intensity in 1 h being 11 mm h^{-1}. Average maximum temperatures per month were 25.1 °C in June, 27.4 °C in July and 26.8 °C in August. Thus the years 2003 and 2004 were exceptionally warm and dry, allowing the analysis of vegetation dynamics during extreme climatic conditions.

During the observation years, neither erosion nor sediment transport occurred in the studied gullies, making it possible to study the vegetation dynamics on sediment deposits without them being recovered by more sediment over these 2 years.

Seed bank in sediment deposits

In all the samples, 154 seedlings were observed, 67 in gully 1 and 86 in gully 2 (Table 1). Expressed by area, the number of plants was 80/m^2 on average, with a maximum value of 148/m^2 (BW10–13 in gully 1) and a minimum value of 0/m^2 (BW7–9 in gully 1). Plants germinated in all the samples except in samples corresponding to BW7–9 in gully 1.

The total number of species was 14 in all the samples, 9 in gully 1 and 11 in gully 2. The highest number of species was found above BW8–10 in gully 2 (7 species). Dicotyledons made up the major part of all the plants that germinated. All the observed species were grasses except one shrub species, the restharrow, and one tree species, the black locust (*Robinia pseudacacia*). *Oxalis corniculata*, the Asteraceae, *Robinia pseudacacia*, *Anthyllis vulneraria*, *Achnatherum calamagrostis* were the most abundant species.

Vegetation recovery on sediment deposits

Considering the two marly gullies in 2003, we found 559 plants on all the bioengineering works, 203 in gully 1 and 356 in gully 2 (Table 2). Expressed by area, the number of plants was $31/m^2$ on average, with a maximum value of $65/m^2$ (BW1–4 in gully 2) and a minimum value of $11/m^2$ (BW7–9 in gully 1).

In 2004, we found 323 plants over the entire bioengineering works area in both gullies, with 96 plants in gully 1 and 227 in gully 2. Expressed by area, the number of plants was $20/m^2$ on average, with a maximum value of $51/m^2$ (BW1–4 in gully 2) and a minimum value of $4/m^2$ (BW4–6 in gully 1).

For all the bioengineering works, there was a general decline in plant abundance between 2003 and 2004 (Figure 2). Considering the variation at the gully scale (all the bioengineering works), plant abundance slightly decreased between 2003 and 2004 only at the gully scale: for gully 1 ($T = 15$, fd.12, $P = 0.03$) and for gully 2 ($T = 24$, fd.15, $P = 0.02$).

Regarding species richness in 2003 (Table 2), we identified 38 species growing on all the mounds, 19 in gully 1 and 34 in gully 2. BW7–9 in gully 1 and BW14–16 in gully 2 showed the poorest species richness (both with seven species). The highest values were found in BW5–7 in gully 2 (20 species). The Asteraceae are well represented herbaceous species, especially with *Crepis* spp. (62 plants) and *Hieracium* spp. (61 plants). *Achnatherum calamagrostis* (Poaceae) was the most abundant grass species (74 plants) growing in the two gullies. The most abundant shrub was the restharrow (37 plants), and we also found Rosaceae shrubs with *Crataegus monogyna* (12 plants) and *Rosa sempervirens* (four plants). We found three species of tree, mainly the Austrian black pine with 37 plants, the opalus maple and the gean (*Prunus avium*), both with one plant.

In 2004, we found 39 species, 21 in gully 1 and 36 in gully 2. The poorest species richness was found above BW4–6 in gully 1 (five species). The highest number of species was on BW1–4 (24 species). For species richness, there was a general declining tendency between 2003 and 2004, but no significant differences (gully 1: $T = 4.0$, fd.12, $P = 0.34$; gully 2: $T = 16$, fd.15, $P = 0.07$) (Figure 3). The Asteraceae family was still well represented on all the sediment deposits

Table 1. Species list, plant abundance and species richness of plants that germinated from the soil cores of bioengineering works. Unidentified seedlings are listed below like others (the exponent number in brackets refers to different morphs)

Bioengineering works (BW) n°	Gully 1				Gully 2				
	1–3	4–6	7–9	10–13	1–4	5–7	8–10	11–13	14–16
Species									
Achnatherum calamagrostis P. Beauv	2	-	-	1	3	1	-	-	-
Anthyllis vulneraria L.	-	1	-	-	-	1	2	2	3
Aphyllantes monspeliensis L.	-	-	-	-	-	1	1	-	-
Asteraceae	1	3	-	4	2	-	1	2	-
Astragalus semperviens Lamarck	-	-	-	2	-	-	-	-	-
Carex ornithopoides L.	2	-	-	-	-	-	-	-	-
Galium sp.	-	-	-	-	-	-	-	-	1
Hieracium pilosella L.	-	-	-	-	-	-	1	1	4
Ononis fruticosa L.	-	-	-	2	-	1	-	-	-
Oxalis corniculata L.	2	-	-	6	7	1	3	-	5
Potentilla reptans L.	-	-	-	-	-	-	2	-	-
Robinia pseudacacia L.	3	-	-	1	-	-	4	1	4
Trifolium sp.	1	-	-	-	1	-	-	-	-
Others	$12^{(6)}$	$3^{(2)}$	0	$21^{(5)}$	$14^{(4)}$	$6^{(2)}$	$3^{(3)}$	$3^{(1)}$	$5^{(4)}$
Plant abundance (total)	23	7	0	37	27	11	17	9	22
Plant abundance ($/m^2$)	123	37	0	148	108	59	80	48	117
Species richness	$6^{(12)}$	$2^{(4)}$	0	$6^{(11)}$	$4^{(8)}$	$5^{(7)}$	$7^{(10)}$	$4^{(5)}$	$5^{(9)}$

Table 2. Species list, plant abundance and species richness of the standing vegetation found on sediment deposits above bioengineering works in 2003 and 2004

Bioengineering works (BW) n°	2003									2004								
	Gully 1				Gully 2					Gully 1				Gully 2				
	1–3	4–6	7–9	10–13	1–4	5–7	8–10	11–13	14–16	1–3	4–6	7–9	10–13	1–4	5–7	8–10	11–13	14–16
Species																		
Acer opalus Miller	1	-	-	-	-	-	-	-	-	1	-	-	-	-	-	-	2	-
Achnatherum calamagrostis P. Beauv	30	5	5	2	2	3	11	16	-	17	3	2	-	-	-	1	2	7
Anthyllis vulneraria L.	8	-	-	1	-	-	1	-	-	4	-	-	-	1	-	-	-	-
Aphyllantes monspeliensis L.	-	-	-	-	11	-	-	-	-	-	-	-	2	-	-	-	-	-
Astragalus monspessulanus L.	1	-	-	-	-	-	-	-	-	1	-	-	-	1	-	-	-	-
Astragalus sempervirens Lamarck	-	-	-	-	-	1	-	4	-	-	-	-	-	-	1	-	1	-
Brachypodium pinnatum L. Beauv.	-	-	-	-	15	-	-	-	-	-	-	-	-	21	-	-	-	-
Bromus erectus Huds.	-	-	-	-	2	-	-	-	-	-	-	-	-	8	3	-	-	-
Calystegia sepium L. R. Br.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	10	-
Carex ornithopoides L.	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Chrysanthemum sp.	-	-	-	-	-	-	-	-	-	-	-	-	-	6	-	-	-	-
Clematis vitalba L.	-	-	-	-	-	-	-	16	-	-	-	-	-	-	-	-	-	-
Cornus sanguinea L.	-	-	-	-	-	-	5	-	-	-	-	-	-	-	-	5	-	-
Crataegus monogyna Jacq.	-	6	1	-	3	1	-	-	1	1	1	-	-	3	3	-	-	-
Crepis pyrenaica (L.)W.Greuter	-	-	-	2	-	-	-	-	17	-	-	-	-	-	-	-	-	-
Crepis sp.	10	1	-	-	14	4	3	10	1	2	-	-	-	6	-	6	-	-
Dactylis glomerata L.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-
Dicotyledons*	-	-	-	-	12	1	-	1	-	-	-	-	-	-	-	-	-	-
Euphorbia cyparissias L.	3	-	-	-	-	3	6	-	-	-	-	-	-	1	-	-	-	-
Galium sp.	-	-	-	-	3	4	1	-	17	-	-	-	-	3	2	1	1	-
Genista cinerea Villars (De Candolle)	-	-	-	1	-	2	-	-	-	-	-	-	1	-	2	-	-	1
Geranium robertianum L.	-	-		-	-	2	-	-	-	-	-	-	-	-	-	-	-	-
Globularia nudicaulis L.	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Hieracium bifidum Hornem	6	-	-	-	13	15	8	7	2	8	2	1	3	5	4	4	8	7
Hieracium pilosella L.	-	-	-	-	10	-	-	-	-	-	-	-	-	10	-	-	-	-
Hippophae rhamnoides L.	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	-
Inula conyza DC.	-	-	-	-	-	-	-	-	-	-	-	-	-	1	-	-	-	1
Juniperus communis L.	-	-	-	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Lactuca perennis L.	-	-	-	-	-	-	-	-	-	-	-	-	-	3	-	-	-	2
Laserpitium gallicum L.	-	-	-	-	3	-	1	3	-	-	-	-	2	2	1	-	3	1
Lavandula angustifolia Miller	-	-	-	-	-	-	3	2	-	1	-	1	-	-	-	1	2	-
Lotus corniculatus L.	1	-	-	-	2	1	-	-	-	1	2	2	-	2	-	-	-	-
Medicago falcate L.		-	-	-		-	-	-	-	-	-	-	-	1	-	-	-	-
Ononis fruticosa L.	2	8	3	6	8	1	2	6	1	8	-	3	2	6	2	-	1	3
Ononis rotundifolia L.	2	2	-	-	-	-	-	-	-	3	-	2	-	2	-	-	-	-
Pinus nigra ssp. nigra J.F Arnold	7	9	1	1	9	2	2	3	3	-	-	-	-	1	-	1	-	-
Potentilla reptans L.	-	-	-	-	-	2	-	-	-	1	-	-	-	-	3	-	-	-
Prunus avium L.	-	-	-	-	1	-	-	-	-	-	-	-	-	15	2	-	-	-
Quercus pubescens Willd.	-	-	-	-	-	-	-	-	-	1	-	-	-	1	-	1	-	-
Rosa sempervirens L.	-	-	3	1	-	-	-	-	-	1	-	2	1	-	-	-	-	-
Sanguisorba minor Scopoli.	7	1	-	1	11	6	11	2	-	2	-	1	2	5	1	6	2	-
Teucrium chamaedrys L.	-	-	-	-	-	7	-	-	-	-	-	-	-	-	5	-	-	-
Thymus serpyllum L.	-	-	-	3	4	5	-	-	-	-	-	-	3	5	2	-	-	-
Trifolium pratense L.	22	12	4	4	1	-	-	-	-	4	1	-	-	-	-	-	-	-

Table 2. Continued

Bioengineering works (BW) n°	2003									2004								
	Gully 1				Gully 2					Gully 1				Gully 2				
	1–3	4–6	7–9	10–13	1–4	5–7	8–10	11–13	14–16	1–3	4–6	7–9	10–13	1–4	5–7	8–10	11–13	14–16
Viburnum lantana L.	-	-	-	-	1	-	-	-	-	-	-	-	-	1	-	-	-	-
Viola hirta L.	1	4	5	10	-	-	2	-	-	1	-	-	-	-	-	3	-	-
Plant abundance (total)	101	48	22	32	125	63	56	70	42	57	9	14	16	110	32	29	34	22
Surface area (m^2)	2,55	2,94	1,78	1,19	2,95	2,05	2,56	3,2	1,54	2,55	2,94	1,78	1,19	2,95	2,05	2,56	3,2	1,54
Plant abundance (/m^2)	60	19	11	28	65	30	25	22	21	35	4	15	16	51	14	12	14	23
Species richness	14	9	7	11	19	20	13	11	7	17	5	8	8	24	14	10	11	7

*Dicotyledons were unidentified seedlings.

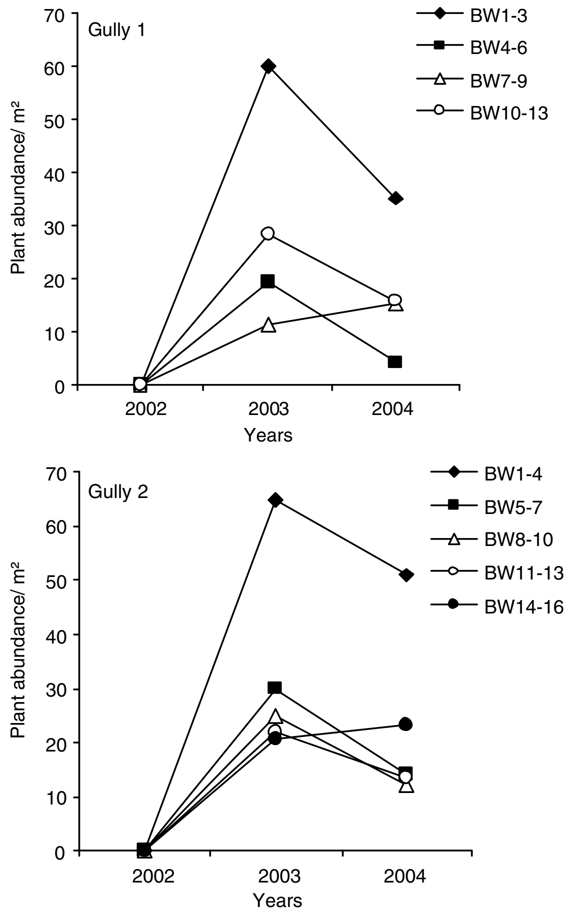

Figure 2. Variation in plant abundance of the standing vegetation since the construction of the bioengineering works in the two marly gullies. Each point represents the mean plant number/m^2 growing on the sediment deposit above the bioengineering works (BW) in 2003 and 2004 (n = number of bioengineering works). No significant differences were shown between the years 2003 and 2004 (standard errors are not represented).

with the genera *Hieracium* (52 plants) and *Crepis* (14 plants), the latter being much less present in 2004 than in 2003. *Achnatherum calamagrostis* was the most abundant species (32 plants), but the number of these plants was halved compared

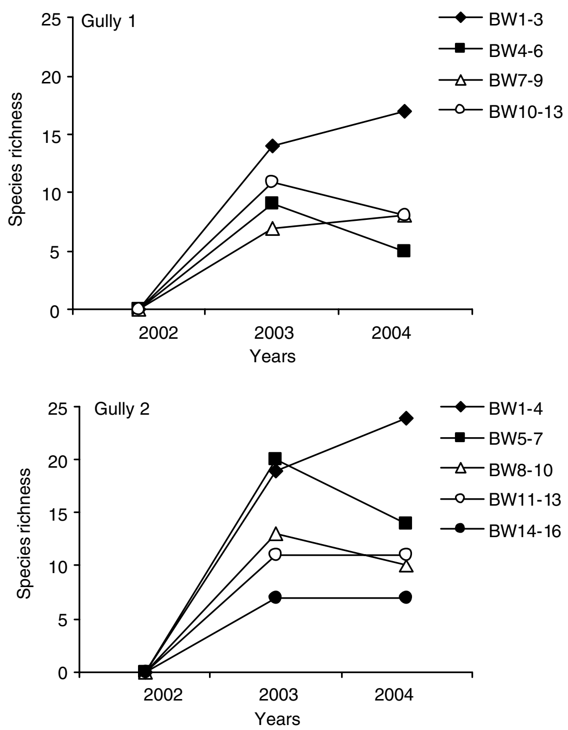

Figure 3. Variation in species richness of the standing vegetation since the construction of the bioengineering works in the two marly gullies. Each point represents the number of species growing on the sediment deposit above the bioengineering works (BW) in 2003 and 2004 (n = number of bioengineering works). No significant differences were shown between the years 2003 and 2004 (Standard errors are not represented).

to 2003. The abundance of many species strongly decreased (*Aphyllanthes monspeliensis*, *Euphorbia cyparissias*, *Galium* sp., *Sanguisorba minor*, *Trifolium pratense*, *Viola hirta*), whereas others became more abundant (*Bromus erectus*) or even appeared for the first time (*Calystegia sepium*, *Chrysanthemum* sp., *Lactuca perennis*). The most abundant shrub was still the restharrow (25 plants), and we observed quite the same shrub species with similar abundance as in 2003, except two plants of *Hippophae rhamnoides* that installed in 2004. We found one more tree species than in 2003, the downy oak (*Quercus humilis*), with three individuals. Only two plants of Austrian black pine were observed, vs. 37 in 2003. On the contrary, 17 plants of opalus maple were found in 2004 vs. only one in 2003.

When we compared similarity in species composition between 2003 and 2004 (Figure 4), BW1–3 in gully 1, BW8–10 and BW1–4 both in gully 2 showed the highest values of similarity (63.2%, 47.4% and 36.6%, respectively). In the other bioengineering works, less than 30% of species persisted from one year to the next.

Effect of water supply improvement on germination

The results concerning the effect of water supply improvement on germination are illustrated in Figure. 5. They showed an increasing trend in the mean number of plants by area for nearly all the bioengineering works (except BW7–9 in gully 1). In particular, the increase was statistically significant for BW10–13 in gully 1 ($F=21.4$, fd.18, $P<0.05$) and BW14–16 in gully 2 ($F=9.1$, fd.18, $P<0.05$). We can note that the black locust and *Oxalis corniculata* were present in the germination experiment (13 and 24 plants, respectively), whereas no plants were observed on the mounds.

Discussion

Natural colonisation by vegetation was observed on sediment deposits, with various plant species developing, thus showing positive vegetation dynamics, even on mineral marly substrates and in a Mediterranean climate in exceptionally dry years. The results show that bioengineering works are able to trap seeds, thereby making a seed bank. This is similar to the results of Urbanska (1997), who observed that structures installed perpendicular to the slope trapped and retained seeds effectively. This also confirms what was established by Guerrero-Campo and Montserrat-Marti (2000), who stated that stable ground can favour vegetation installation and development, whereas erosion processes generally prevent these processes (Chambers, 2000; Cohen and Rey, 2005).

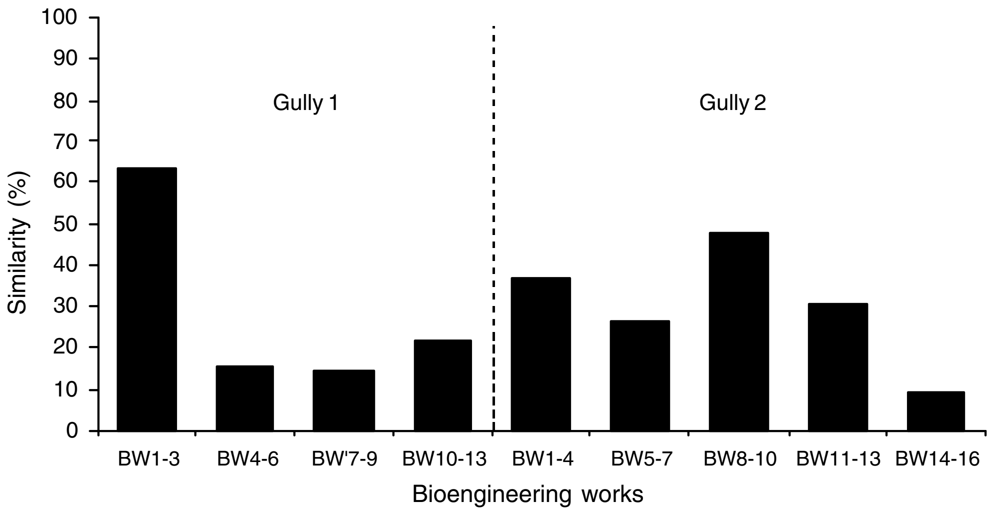

Figure 4. Percentage similarity in standing vegetation based on species presence/absence between 2003 and 2004 on bioengineering works.

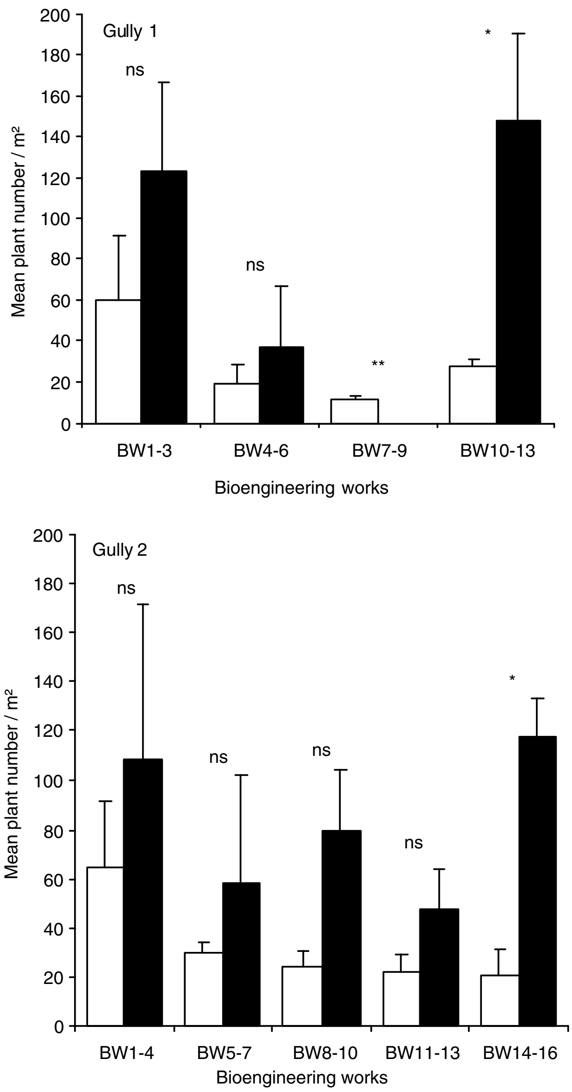

Figure 5. Comparison between standing vegetation and seed bank showing the effects of non-limited water treatment on plant abundance. Mean ($\pm$SE, $n=3$) plant number expressed by m^2 of sediment deposit above bioengineering works in the two marly gullies (black column: mean number of plants in soil cores; white column: mean number of plant on sediment deposit). Stars indicate a significant effect of the treatment for each bioengineering work, $*P<0.05$, $**P<0.01$, $***P<0.001$, ns: no significant effect.

However, it is difficult to evaluate the significance of plant abundance based solely on the number of plants. It would have been more useful to estimate the vegetation cover, but plants were not developed enough to measure this. In general, vegetation covers in the mounds were less than 5% after 2 years, a rather low figure. Moreover, plant abundance diminished between spring 2003 and spring 2004, certainly because of the dry summer in 2003. As the summer of 2004 was also very dry, plant abundance may again decrease in 2005. In case of similar climate conditions occurring in the coming years, natural colonisation on mounds should be very slow.

Diversity was rather good, on the mounds as well as in the laboratory. In particular, we observed the development of species that aid in sediment trapping (Rey et al., 2004): grasses, *Achnatherum calamagrostis* and *Aphyllanthes monspeliensis*, and shrubs, *Ononis fruticosa* and *Hippophae rhamnoides*. *Brachypodium pinnatum* and *Bromus erectus*, which have the same morphology as *Achnatherum calamagrostis*, should also act as effective vegetation barriers (Bochet et al., 2000). Investigating how these plants will develop with time would determine whether they lead to the formation of natural vegetation barriers that could trap sediment. Thus, after the use of *Salix* species, the pioneer plants, these colonising plants could make up the post-pioneer vegetation. It appears that the main dissemination factor of these colonising plants is gravity, with superficial micro-landslides bringing with them plants present on gully walls. These results show that plant successions that could lead to sustainable recovering of marly gully floors with vegetation should be considered. Biodiversity should be maintained in the coming years to favour stable and sustainable ecosystems. Trees such as black locust, maple and Austrian black pine can have greater ecological and structural impacts on the bioengineering works.

Germination experiments show that an improvement in soil water conditions slightly increases the capacity of the sediment deposits to allow seed germination. As the two observation years were very dry and warm on the field sites, we surmise, as explained by Cerdà and Garcia-Fayos (2002), that the harsh climatic conditions, and especially the poor water availability, were responsible for the lack of germination, as well as the decreasing number of seedlings between 2003 and 2004. However, the results were not significant for all the bioengineering works. The results are nevertheless quite promising, because the bioengineering works efficiently improved soil conditions to allow germination. Moreover, samples collected in the field were certainly not representative of the whole seed bank present within the mounds. Therefore, it is difficult to assess if adding water and organic matter to the sediment deposits would significantly improve the vegetation dynamics. The high cost of these operations makes their use debatable.

These results do not reflect high effectiveness over the short term of natural vegetation for sediment trapping during future rainfall events. It may therefore be necessary to consider further rehabilitation action. Brush mats, which are covers of cuttings installed in the same way as brush layers, can be installed directly on the sediment deposits, in order to revegetate them very quickly and effectively, but this will raise the cost of rehabilitation actions.

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