

HOW CAN WE CONTROL EROSION OF ROADSLOPES IN SEMIARID MEDITERRANEAN AREAS? SOIL IMPROVEMENT AND NATIVE PLANT ESTABLISHMENT

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Received 18 September 2008; Revised 5 January 2009; Accepted 6 January 2009

ABSTRACT

Road building triggers vegetation and soil degradation which affects road safety. We present conclusive results in terms of roadslope protection against erosion from several studies performed on semiarid roadslopes since 2000 (in Eastern Spain). We aim to (1) improve our understanding about slope and vegetation factors which control soil erosion and plant colonisation on semiarid roadslopes; (2) assess the effectiveness of topsoiling, hydroseeding and species selection in the protection of soil against erosion and (3) set scientifically based priorities on ecosystem components that have to be taken into account in future roadslope restoration plans.

Erosion and vegetation cover estimations, vegetation surveys, drilling and hydroseeding experiments with commercial and native species were performed on roadslopes, in addition to seed germination and root penetration experiments.

Our results indicate that slope type and angle are the main factors controlling soil erosion and plant colonisation on semiarid roadslopes. Microsite availability is more limiting to plant establishment than seed availability. Restoration strategies based on the improvement of soil properties and the appropriate selection of native species, able to overcome harsh hydrological and structural soil conditions, are proposed and tested according to slope characteristics. Drilling proved to be a promising technique for roadcut restoration, whereas topsoiling followed by hydroseeding with a seed mixture of selected native species was the most efficient treatment, in terms of cost and benefit, to control erosion on roadfills.

This study clearly shows that ecological knowledge is needed to guide restoration efforts in Mediterranean ecosystems. Moreover, an efficient transfer of scientific knowledge from researchers to the institutions concerned (restorers, policymakers and practitioners) is also needed in the perspective of a more appropriate management of these ecosystems. Copyright © 2009 John Wiley & Sons, Ltd.

KEY WORDS: vegetation cover; hydroseeding; ecological restoration; plant colonisation; Mediterranean environment; topsoil; water holding capacity; soil compaction

INTRODUCTION

Over the recent decades, the increasing worldwide road network has been superimposed upon the land to provide efficient human mobility and merchandise transportation. However, this development, which aims to improve human well-being, results in land degradation with significant impacts upon plant communities and soil stability, such as increased soil erosion and sediment deposition, habitat fragmentation and altered plant community structure (Forman and Deblinger, 2000).

Bare slopes resulting from road construction typically present a hostile environment to spontaneous recolonisation by plants. Thus, to counteract land degradation and stabilise the roadslopes, revegetation projects are

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frequently undertaken, after road construction, to enhance the rapid establishment of a plant community able to control erosion. Among the various techniques used for roadslope revegetation, hydroseeding is one of the most widespread since it is primarily aimed at stabilising soil and controlling water erosion in the very short-term with a fast and dense vegetation cover (Merlin *et al.*, 1999; Robichaud *et al.*, 2000). In most cases, when slope angle is appropriate, hydroseeding is performed after the original top layer of soil has been put back into place. If the topsoil layer has been adequately removed and stored during road construction, it has the advantage of being rich in seeds and organic matter and enhances plant establishment (Merlin *et al.*, 1999; Balaguer, 2002).

However, in dry or semiarid conditions, standard hydroseeding frequently renders poor results and the performance of standard commercial hydroseeded species is usually poor from the very beginning (Andrés and Jorba, 2000; Martínez-Ruiz, 2000). The poor results, obtained up to now, may be due to different factors that influence initial plant establishment such as slope conditions (i.e., slope type, aspect and angle and soil properties), vegetation factors (i.e. availability of seeds, origin of seed sources and selection of species) or the interaction of both, which therefore determines the performance of the hydroseeded species in specific site conditions.

Recent studies point out that advances in restoration ecology are intrinsically linked to advances in the ecological understanding of the ecosystems to be restored and that restoration success can only be guaranteed by an accurate ecological knowledge of soil (physical, chemical and hydrological) and vegetation properties (i.e. Prach, 2003; Temperton *et al.*, 2004; Valladares and Gianoli, 2007). However, the transfer of information between restoration ecologists and practitioners about which ecosystem features (factors, processes) facilitate or hinder restoration is scarce (Schaffers and Sykora, 2002; Méndez *et al.*, 2008). In the last decade, practitioners have asked researchers to examine such problems experimentally in order to provide not only important site-specific recommendations, but also potentially useful generalisations (Clewett and Rieger, 1997). This study attempts to answer this request on the basis of a synthesis of several experiments performed since 2000 in a semiarid Mediterranean area of Eastern Spain. The general objective is to provide guidelines for the restoration of semiarid Mediterranean roadslope ecosystems based on the scientific knowledge of the ecosystem ecological and geomorphological functioning. Our specific objectives are:

- (1) to improve our understanding of the factors that control soil erosion and plant establishment on semiarid Mediterranean roadslopes, emphasising roadslope factors (slope type, aspect and angle and soil properties), vegetation factors (dispersal limitations) and the interaction of both (response of plants to adverse soil conditions such as soil compaction or water stress);
- (2) to assess the effectiveness of topsoiling, hydroseeding after topsoiling, species selection for revegetation projects and drilling in the protection of the soil against erosion on roadslopes;
- (3) to define, on a scientific basis, the priorities upon the ecosystem components that have to be taken into account in future roadslope restoration plans.

MATERIAL AND METHODS

Study Area

The area where the study was conducted was the Region of Utiel-Requena in Eastern Spain (39°29' N; 1° 06' W), which is in the geographical Mediterranean Region. It is representative of large areas of inner Spain with semiarid climatic conditions. Mean annual precipitation and temperature range between 399 mm and 12°C at Utiel and 418 mm and 14.2°C at Requena, respectively. Rainfall is at highest in October. Droughts are common in summer and frosts in winter (Pérez, 1994). The lithology consists of calcareous marls and clays of Tertiary age. Vineyards and dry farming are the dominant land uses in the area with small scattered patches of remnant natural Mediterranean shrubland.

Two different roadslope systems were selected to carry out the different experiments between 2000 and 2007: the A3-highway between km 267 and 307 and N-330 road between 189 and 190 km. Both systems were lithologically

EROSION MITIGATION IN SEMIARID ROADSLOPES

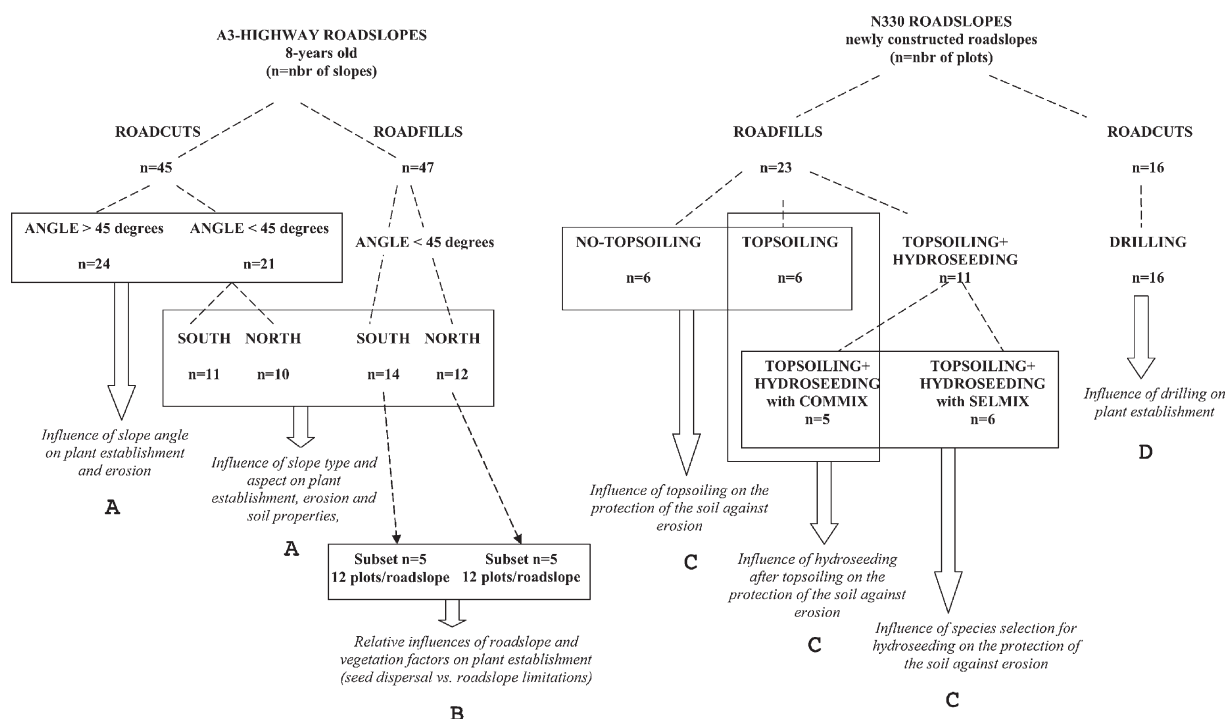


Figure 1. General diagram of the sampling design for the whole set of field experiments performed between 2000 and 2007. Capital letters (A–D) refer to the ‘Material and Methods’ Section where the corresponding methodology is described (letters between brackets after the methods titles).

and climatically homogeneous. Eight-year-old roadslopes with established vegetation were selected in the A3-highway to achieve the first objective, i.e. the identification of the factors that control plant establishment and erosion on roadslopes. Also, newly constructed and almost unvegetated roadslopes of the N-330 were used to achieve the second objective, i.e. to test and determine the effectiveness of different restoration techniques to protect the soil against erosion. All roadslopes were larger than 20 m long, 5 m high and 25 degrees steep and with less than 5 per cent of rock outcrops. The sampling design of roadslopes is given in Figure 1.

Influence of Slope Factors on Plant Establishment, Erosion and Soil Properties (see “A” in Figure 1)

To determine the influence of the slope on erosion and plant establishment, different subgroups of roadslopes were considered according to their construction characteristics (angle, type and aspect, see Figure 1). The influence of slope angle was determined comparing two homogeneous groups of roadcuts of the same origin (both excavated) but with different angles (>45 and <45 degrees). The influence of slope type and aspect was determined within a homogeneous set of slopes < 45 degrees. Within this latter group, roadslope soil conditions were studied by analysing soil texture, organic matter, total nitrogen, available phosphorous, soil compaction, soil moisture dynamics and soil water holding capacity. Soil texture, organic matter, total nitrogen and available phosphorous were determined by the hydrometer method of Gee and Bauder (1986), the Walkley–Black method, the Kjeldahl method and the Olsen method, respectively (all described in Page *et al.*, 1982). Soil compaction, water holding capacity and soil moisture dynamics were determined by means of a handpenetrometer, the Richard’s standard pressure chamber procedure (Klute, 1986) and humidity sensors, respectively.

Plant establishment success was expressed in terms of total vegetation cover and species success in roadslopes. Total vegetation cover accounted for spontaneous colonising species from adjacent areas and species hydroseeded by the public administration at the time roadslopes were built (8 years earlier). Species success was assessed by

taking into account the frequency and abundance of all the species listed in the sampled roadslopes. Frequency was defined as the percentage of roadslopes in which a species was present and abundance as the relative abundance of each species in each roadslope according to pre-established abundance classes (class 0: species absent; 1: less than 10 individuals scattered along the slope; 2: individuals present either regularly or in local monospecific patches and 3: species present abundantly along the slope). Species establishment was considered successful if the species was present in more than 50 per cent of the sampled roadslopes and if it was present either regularly or in local large monospecific patches in at least one third of the roadslopes where the species was present. When a species did not fulfil the requirements, it was considered unsuccessful.

The severity of erosion was estimated by means of an erosion index defined as the extent to which a roadslope area was affected by rill erosion, gully erosion and mass movement processes (separately for the different sub-processes and jointly for overall erosion). A more detailed description of the method used is given in Bochet and García-Fayos (2004).

Relative Influences of Roadslope and Vegetation Factors on Plant Establishment (see “B” in Figure 1)

Manual sowing experiment: seed dispersal versus roadslope limitations

Sowing experiments were performed manually to determine the most limiting factors upon plant establishment on roadslopes. The relative influences of seed dispersal (seed ability to disperse to a long distance and reach the slope from the adjacent natural vegetation) and roadslope characteristics (slope aspect, soil properties) on plant establishment were assessed by sowing two groups of species in $60 \times 65 \text{ cm}^2$ plots. Six successful (1st group) and six unsuccessful spontaneous colonisers (2nd group) were selected according to their establishment success (see previous section). The hypothesis supporting this experiment was that if roadfill conditions are more limiting to plant establishment than seed dispersal from adjacent areas, seed addition of unsuccessful colonisers should lead to lower establishment success than that achieved by the sown successful colonisers in the sowing experiment. Seedling emergence was measured 8 months after sowing. More methodological details are provided in Tormo *et al.* (2006).

Influence of Soil Properties and their Interaction with Vegetation on Plant Establishment

Water-stress and seed germination success

In order to determine whether the success of species establishment on roadslopes and especially south-facing roadcuts, which are the most unfavourable slopes for plant establishment, is due to the ability of seeds to germinate fast at low water potentials, germination characteristics of different species were tested under a soil water potential gradient under laboratory conditions. The effects of five levels of water potential (0; -20 ; -50 ; -350 and -1500 kPa) on the germination time (number of days until the first germination occurred) and rate (percentage of germinated seeds over 33 days) were tested for three groups of species selected according to their establishment success: S or ‘overall successful colonisers’ (successful in the four categories of roadslopes), Rf or ‘roadfill successful colonisers’ (exclusively successful in roadfills) and U or ‘unsuccessful colonisers’ (unsuccessful in the four categories of roadslopes). Groups were compared in pairs to determine the existence of possible roadslope (S vs. U), and more specifically roadcut limitations (S vs. Rf). Germination time was compared with the number of days water remained available in the roadslopes above a specific water potential (equivalent to a soil moisture content measurement determined in the laboratory) to explain the relative success of species establishment in the roadslopes. A more detailed description of the methodology used is provided in Bochet *et al.* (2007).

Soil compaction and root penetration success

In order to determine if soil compaction is limiting to plant establishment on roadslopes, and especially on roadcuts, the capacity of roots from two overall successful species to penetrate different levels of wax layer compaction was tested under laboratory conditions. *Anacyclus clavatus* and *Dactylis glomerata*, a tap- and a branch-rooted species, respectively, were selected. The effect of wax layer compaction on the root penetration time (number of days until

the first penetration occurred) and rate (number of penetrating roots/seed over 33 days) was tested at 60 and 1500 kPa (average levels of soil compaction measured on roadfills and roadcuts, respectively). A more detailed description of the methodology used is provided in Monsalve (2007).

Effectiveness of Different Restoration Techniques in the Protection of the Soil Against Erosion (N-330 roadslopes)

Topsoiling, hydroseeding after topsoiling and species selection for hydroseeding on roadfills (see “C” in Figure 1)
The effect of topsoiling, hydroseeding after topsoiling and species selection for hydroseeding on the protection of the soil against erosion was determined in $4 \times 4 \text{ m}^2$ plots. Plant establishment and erosion severity were compared between roadfills submitted to different treatments. The following treatments were compared two by two as described in Figure 1: ‘topsoiled’ (TS) versus ‘no-topsoiled’ (Ctrl) plots (effect of topsoil addition), ‘topsoiled’ versus ‘topsoiled + hydroseeded’ (TS + HS) plots (effect of hydroseeding after topsoiling), ‘topsoiled + hydroseeded with ComMix’ (TS + HS_Com) versus ‘topsoiled + hydroseeded with SelMix’ (TS + HS_Sel) plots (effect of species selection). ComMix and SelMix refer to the seed mixtures used in the hydroseeding experiment. ComMix consists of standard commercial species widely used in semiarid Mediterranean Spain for roadslope revegetation and SelMix consists of successful native species on roadfills (according to the previous assessment of plant establishment success). The topsoil layer, originally taken from this area, was removed and stockpiled by the public administration for less than 3 months before being put back into place after road construction.

Plant establishment was estimated in terms of total vegetation cover and absolute cover of hydroseeded species included in the seed mixture, in February 2004, June 2004, 2005, 2006 and 2007. A hydroseeding success index (HSI) able to determine the relative contribution of hydroseeded species to the total cover was calculated, as described in Matesanz *et al.* (2006; HSI is the ratio between the absolute cover of hydroseeded species and total vegetation cover in the plot). The severity of erosion was estimated at the same time as visits were carried out for the vegetation cover estimations, except for the February 2004 visit. An erosion index was defined as the proportion of the plot area affected by rills (in classes, see Tormo *et al.*, 2007 for methodological details).

Because the treatments were not fully crossed, the effect of topsoiling, hydroseeding after topsoiling and species selection was analysed separately. Repeated-measure ANOVA was used to determine changes over time in vegetation cover and the cumulative erosion index. Statistical analyses were performed using SPSS v.15.0[®].

Drilling on roadcuts (see “D” in Figure 1)

The effect of changes in soil microtopography on plant establishment was determined by a manual sowing experiment in $65 \times 60 \text{ cm}^2$ plots on steep roadcuts of approximately 45 degrees (see Figure 1D). Changes in microtopography were achieved by drilling the soil with a nail. Seeds of two successful colonisers on south-facing roadcuts, *Plantago albicans* and *Santolina chamaecyparissus*, were placed in the resulting 2–3 mm wide and 3 cm deep holes. Fifty seeds were sown per plot, one per hole. Plant establishment success was measured in terms of seedling establishment and survival 1 year after sowing.

RESULTS

Influence of Slope Factors on Plant Establishment, Erosion and Soil Properties

Plant establishment and erosion

Roadslope angle had a strong influence on vegetation cover and overall erosion index ($U_{\text{MW}} = 58.5$, $p < 0.001$ and $U_{\text{MW}} = 139.0$, $p \leq 0.01$, $n = 45$, respectively, Figures 2 and 3). Mass movement was higher on roadcuts > 45 than on roadcuts < 45 degrees, but no statistical difference existed in the degree of rill and gully erosion between both slope categories ($U_{\text{MW}} = 68.5$, $p < 0.001$; $U_{\text{MW}} = 188.5$, $p = 0.12$; $U_{\text{MW}} = 194.0$, $p = 0.181$, $n = 45$, respectively, Figure 3).

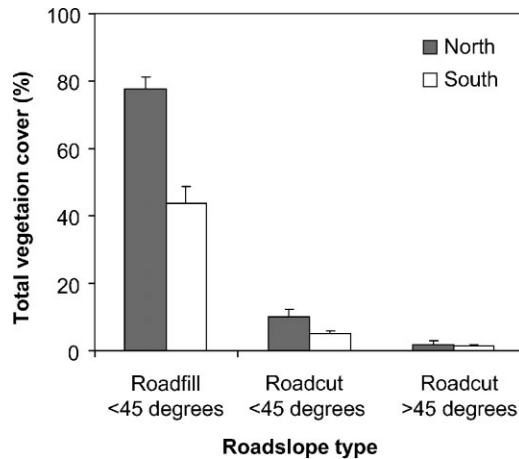


Figure 2. Total vegetation cover (per cent, mean \pm SE) according to the type, aspect and angle of roadslopes. After Bochet and García-Fayos (2004).

Roadslope type and aspect both had a strong influence on vegetation cover of slopes < 45 degrees (Figure 2), with higher cover on roadfills than on roadcuts (59.4 ± 4.7 per cent and 7.4 ± 1.2 per cent, $F_{1,43} = 218.7$; $p < 0.001$, respectively) and higher cover on north-facing slopes than on south-facing ones (47.0 ± 7.8 per cent and 26.7 ± 4.8 per cent, $F_{1,43} = 28.7$; $p < 0.001$, respectively, Figure 2). Contrary to the roadslope aspect ($F_{1,43} = 0.05$, $p = 0.819$), the slope type strongly influenced erosion with more severe erosion on roadcuts < 45 degrees than on roadfills (4.5 ± 0.3 and 2.7 ± 0.2 , respectively, $F_{1,43} = 26.8$, $p < 0.001$, Figure 3). This is mainly due to the higher severity of all erosion sub-processes in roadcuts relative to roadfills, but mass movement ($U_{MW} = 60.5$, $p < 0.001$; $U_{MW} = 162.5$, $p < 0.05$; $U_{MW} = 221.5$, $p = 0.109$, $n = 47$, respectively for rill, gully and mass movement, Figure 3).

Total vegetation cover was negatively and significantly correlated with all erosion sub-processes and with the overall erosion index ($r_{\text{rills}} = -0.736$, $r_{\text{gullies}} = -0.329$; $r_{\text{mass movement}} = -0.315$; $r_{\text{overall erosion}} = -0.675$; $p < 0.001$, $n = 47$ in all cases) indicating that vegetation cover can be used as an indicator of soil protection ability in these slope systems.

Species establishment success was influenced by the slope type and aspect. Among the 324 species recorded in the roadslopes (more details about the species listed in Bochet and García-Fayos, 2004), 49 were successfully established 8 years after road construction, at least in one of the four slope categories studied (north- and south-facing roadcuts or roadfills, Table I). Seventeen species were successful in the four categories of roadslopes.

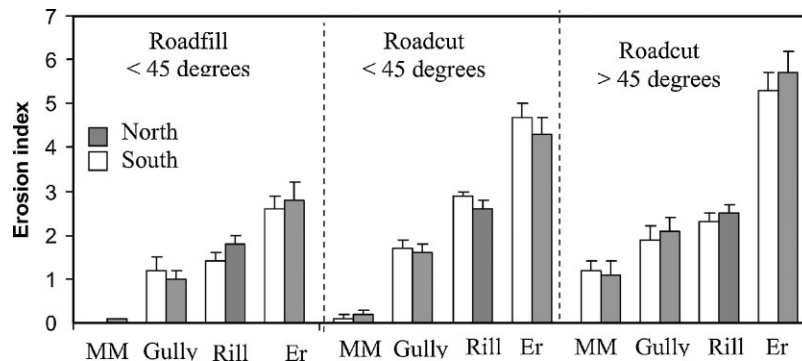


Figure 3. Severity of erosion sub-processes according to roadslope type, aspect and angle. Erosion index (mean \pm SE) was estimated in classes from 0 to 3 according to the roadslope area occupied by rills, gullies and mass movement processes (MM) (0: no erosion, 1: area $\leq 1/3$, 2: area between $1/3$ and $2/3$ and 3: area $> 2/3$ of the total roadslope area). Overall erosion (Er) was defined as the sum of the values obtained for the three erosion sub-processes. After Bochet and García-Fayos (2004).

Table I. Species establishment success of successful species on roadslopes after 8 years according to slope type and aspect

Species name	SRc	NRc	SRf	NRf
<i>Alyssum simplex</i> ; <i>Anacyclus clavatus</i> ; <i>Avena barbata</i> ; <i>Bromus inermis</i> *; <i>Bromus rubens</i> ; <i>Centaurea aspera</i> ; <i>Cichorium intybus</i> ; <i>Convolvulus arvensis</i> ; <i>Dactylis</i> <i>glomerata</i> *; <i>Diplotaxis erucoides</i> ; <i>Euphorbia serrata</i> ; <i>Hordeum murinum</i> subsp. <i>leporinum</i> ; <i>Medicago sativa</i> *; <i>Onobrychis viciifolia</i> *; <i>Sanguisorba minor</i> *; <i>Scabiosa simplex</i> ; <i>Sonchus oleraceus</i>				
<i>Bromus tectorum</i> ; <i>Crepis vesicaria</i> ; <i>Erodium cicutarium</i>				
<i>Calendula arvensis</i> ; <i>Carduus pycnocephalus</i> ; <i>Filago</i> <i>pyramidata</i> ; <i>Medicago minima</i>				
<i>Eryngium campestre</i> ; <i>Lolium rigidum</i> *				
<i>Festuca arundinaceae</i> *				
<i>Scorzonera laciniata</i> ; <i>Silene nocturna</i>				
<i>Reseda phyteuma</i> ; <i>Pallenis spinosa</i> ; <i>Plantago albicans</i>				
<i>Carthamus lanatus</i> ; <i>Crepis foetida</i> ; <i>Foeniculum vulgare</i> subsp. <i>piperitum</i> ; <i>Linaria simplex</i> ; <i>Papaver rhoeas</i> ; <i>Senecio gallicus</i> ; <i>Senecio vulgaris</i>				
<i>Avena sterilis</i> ; <i>Cynodon dactylon</i> *; <i>Erodium ciconium</i> ; <i>Erodium malacoides</i> ; <i>Hirschfeldia incana</i> ; <i>Reseda undata</i>				
<i>Aegilops geniculata</i> ; <i>Aegilops triuncialis</i>				
<i>Genista scorpius</i> ; <i>Santolina chamaecyparissus</i> subsp. <i>squarrosa</i>				

S = south; N = north; Rc = roadcut; Rf = roadfill; Cells in grey indicate success * = hydroseeded species; After Bochet *et al.* (2009).

Soil properties

Slope type significantly influenced the soil variables, but there was no effect of slope aspect or the interaction between slope type and aspect (Table II). Soil chemical, physical and hydrological properties were more favourable in roadfills than in roadcuts. Soil fertility was higher in roadfills than in roadcuts, as expressed by the organic matter ($F_{1,4} = 87.4$,

Table II. Soil characteristics (mean \pm SE) in north- and south-facing roadfills and roadcuts (with angles <45 degrees)

Soil properties	Roadcuts		Roadfills	
	South	North	South	North
Sand (per cent)	32.06 ± 0.87 a	40.84 ± 11.52 a	41.14 ± 7.63 a	35.10 ± 2.67 a
Lime (per cent)	35.80 ± 2.53 a	32.66 ± 6.64 a	24.23 ± 3.52 a	30.73 ± 2.07 a
Clay (per cent)	32.14 ± 1.67a	26.56 ± 4.94 a	37.89 ± 14.31 a	34.18 ± 0.60 a
O.M. (per cent)	<0.8 ¹ a	<0.8 ¹ a	1.5 ± 0.2 b	1.2 ± 0.0 b
N _{total} (per cent)	<0.070 ¹ a	<0.070 ¹ a	0.076 ± 0.002a	<0.070 ¹ a
P _{available} (mg P ₂ O ₅ 100 g soil ⁻¹)	0.5 ± 0.1 a	0.5 ± 0.1 a	3.1 ± 1.4 b	1.9 ± 0.9 b
Compaction (kPa) ²	1560 ± 1180 a		60 ± 10 b	
Water holding capacity (moisture content in per cent V/V)				
At: -20 kPa	21.79 ± 2.23 (0) a	23.35 ± 2.62 (1) a	25.43 ± 1.26 (4) b	27.16 ± 0.68 (4-33)b
-50 kPa	17.63 ± 2.02 (1) a	16.75 ± 1.11 (11)a	20.03 ± 0.72 (13)b	22.02 ± 0.03 (>33)b
-350 kPa	10.50 ± 0.65 (8)a	11.63 ± 1.00 (>33)a	14.25 ± 0.65 (>33)b	14.37 ± 1.33 (>33)b
-1500 kPa	8.92 ± 1.50 (8)a	8.42 ± 0.59 (>33)a	11.05 ± 0.47 (>33)b	12.32 ± 0.52 (>33)b
(Between brackets: number of consecutive days water content remained in the topsoil layer above this value after an 8-day rain event of 491.m ⁻²)				

¹Lower than the level of detection of the method used (the values corresponding to the level of detection were used for the statistical analyses).

²Soil compaction measurements performed on another set of roadslopes with similar lithological characteristics, but without taking into consideration the slope aspect. Values with the same letter (within each soil property) do not differ significantly from one another ($p < 0.05$). After Bochet and García-Fayos (2004) and Bochet *et al.* (2007).

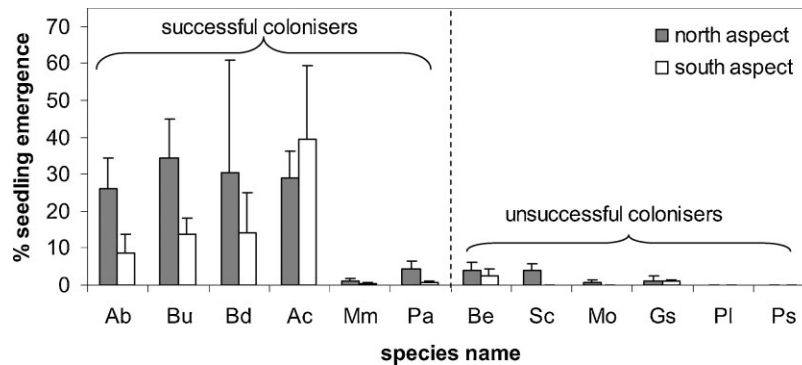


Figure 4. Seedling emergence rate (per cent, mean \pm SE) according to species establishment success (successful vs. unsuccessful) and slope aspect (north vs. south). (Successful species: Ab = *Avena barbata*, Bd = *Bromus diandrus*, Bu = *Bromus rubens*, Ac = *Anacyclus clavatus*, Mm = *Medicago minima*, Pa = *Plantago albicans*; unsuccessful species: Be = *Brachypodium retusum*, Sc = *Santolina chamaecyparissus*, Mo = *Medicago orbicularis*, Gs = *Genista scorpius*, Pl = *Plantago lanceolata*, Ps = *Plantago sempervirens*). After Tormo *et al.* (2006).

$p < 0.001$), available phosphorus ($F_{1,4} = 10.7$, $p < 0.001$), and total nitrogen contents ($F_{1,4} = 4.9$, $p = 0.09$). The topsoil layer was much less compacted in roadfills than in roadcuts ($t = -14.2$, $df = 105$, $p < 0.001$). Soil moisture was higher at all water potentials in roadfills than in roadcuts ($F = 49.529$; $p < 0.001$). Moreover, an increasing gradient of soil drying speed was detected in the order: north roadfill, south roadfill, north roadcut and south roadcut. For example, moisture content remained in the soil above a specific value determined in the laboratory at -50 kPa for only 1 day in south-facing roadcuts, 11 consecutive days in north-facing roadcuts, 13 consecutive days in south-facing roadfills and more than 1 month in north-facing roadfills after an intense rainfall event (Table II).

Relative Influences of Roadslope and Vegetation Factors on Plant Establishment

Manual sowing experiment: seed dispersal vs. roadslope limitations

Seedling emergence after the addition of seeds on roadfills was over ten times greater for successful than for unsuccessful species ($\chi^2 = 986$, $df = 1$, $p < 0.05$, Figure 4), indicating that roadfill conditions are more limiting to plant establishment than seed dispersal from adjacent areas. As the experiment was performed on relatively gentle slopes (< 45 degrees), roadfill conditions refer here mainly to the soil conditions rather than to the slope angle. Seedling emergence was not significantly affected by the slope aspect ($\chi^2 = 71$, $df = 1$, $p = 0.06$).

Influence of Soil Properties and Their Interaction with Vegetation on Plant Establishment

Water-stress and seed germination success

Mean germination rates of S-species were higher than those obtained for U- and Rf- species at all water potentials ($t = 5.285$, $p < 0.001$ for S- vs. U-species and $t = 2.385$, $p < 0.05$ for S- vs. Rf-species). The significant effect of the interaction factor 'success \times water potential' on the germination speed ($t = -5.740$ for S- vs. U-species and $t = -7.855$ for S- vs. Rf-species, $p < 0.001$) indicates that differences in the first day of germination within these two pairs of species groups occurred at -350 kPa, but not at less negative water potentials (Figure 5).

Moreover, dynamics of soil moisture in the roadslope reveal that roadslopes are in water-stress conditions most of the time during the germination period. Only 10 rainfall events were able to moisten the soil above -350 kPa during the two successive germination periods studied and the number of days water remained in the soil after the most intense rainfall event was low at all water potentials in south-facing roadcuts and above -350 kPa for the other roadslope categories (Table II). These results seem to indicate that seed germination in roadslopes usually occurs at water potentials lower than -50 kPa and higher than -1500 kPa for species that are able to germinate in a time lower than the number of days water remains in the soil above these water potentials. This is the case of S-species that germinated at -350 kPa in a lower number of days (6 days in average and 50 per cent germination rate,

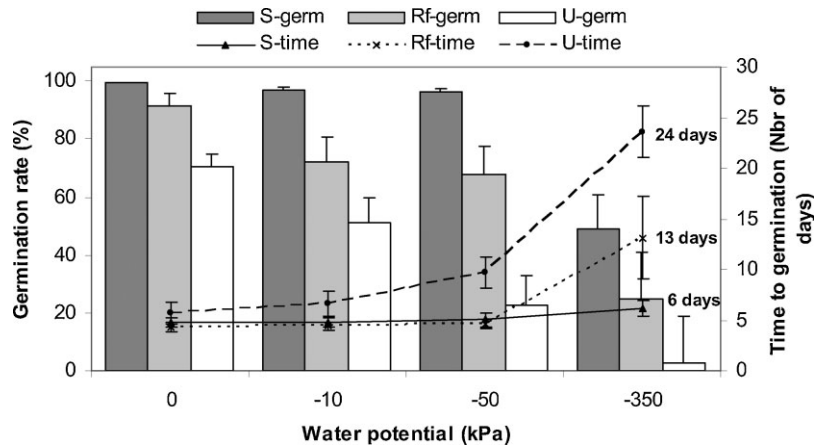


Figure 5. Germination rate (per cent, mean \pm SE) and time to first germination (number of days, mean \pm SE) for successful colonisers in all roadslope categories (S), colonisers exclusively successful in roadfills (Rf) and unsuccessful colonisers in all roadslope categories (U). No single germination was observed in the laboratory at -1500 kPa. After Bochet *et al.* (2007).

Figure 5) than the number of days water content remained in the roadslopes above -350 kPa, even in south-facing roadcuts (8 days, Table II). However, this is not the case of Rf- and U-species, which needed, in the same conditions, 13 and 24 days in average, respectively, to germinate with very low germination rates (25 and 5 per cent respectively, Figure 5).

Soil compaction and root penetration success

Roots of both species were able to penetrate, within few days, a level of compaction similar to that measured in roadfills (60 kPa), but no single root was able to penetrate a level of compaction of 1500 kPa similar to that measured in roadcuts ($U_{MW} = 0$, $p < 0.001$, $n = 20$; Table III).

Effectiveness of Different Restoration Techniques in the Protection of the Soil Against Erosion

Topsoiling, hydroseeding after topsoiling and species selection for hydroseeding on roadfills

Topsoiling. Total vegetation cover increased through the study period in the Ctrl and TS plots ($F_{4,40} = 114.48$, $p < 0.001$ for time), but it was higher in the TS than in the Ctrl ones with the highest difference occurring in June 2004 after the first growing season ($F_{1,10} = 7.18$, $p < 0.05$ for treatment and $F_{4,40} = 3.89$, $p = 0.05$ for the interaction, Figure 6A). However, cumulative erosion increased similarly in both treatments through the study period ($F_{1,10} = 0.41$, $p = 0.54$ for treatment; $F_{4,40} = 198.28$, $p < 0.001$ for time and $F_{4,40} = 1.39$, $p = 0.27$ for the interaction, Figure 6B).

Table III. Root penetration rate (number of roots/seed, mean \pm SE) and speed (number of days, mean \pm SE) in 7 mm deep wax layer according to the compaction level and species

	<i>Anacyclus clavatus</i> (tap-rooted)		<i>Dactylis glomerata</i> (branched-rooted)	
	Compaction		Compaction	
	60 kPa ($n = 5$)	1500 kPa ($n = 5$)	60 kPa ($n = 5$)	1500 kPa ($n = 5$)
Penetration rate	1.3 ± 0.1	0	1.9 ± 0.2	0
Time to penetration	2.0 ± 0.2	—	2.0 ± 0.3	—

Compaction levels simulate roadfill (60 kPa) and roadcut (1500 kPa) average soil compaction. —: No time data because no penetration occurred at that compaction level. Each replicate is the average value of 25 seeds placed on a wax disc.

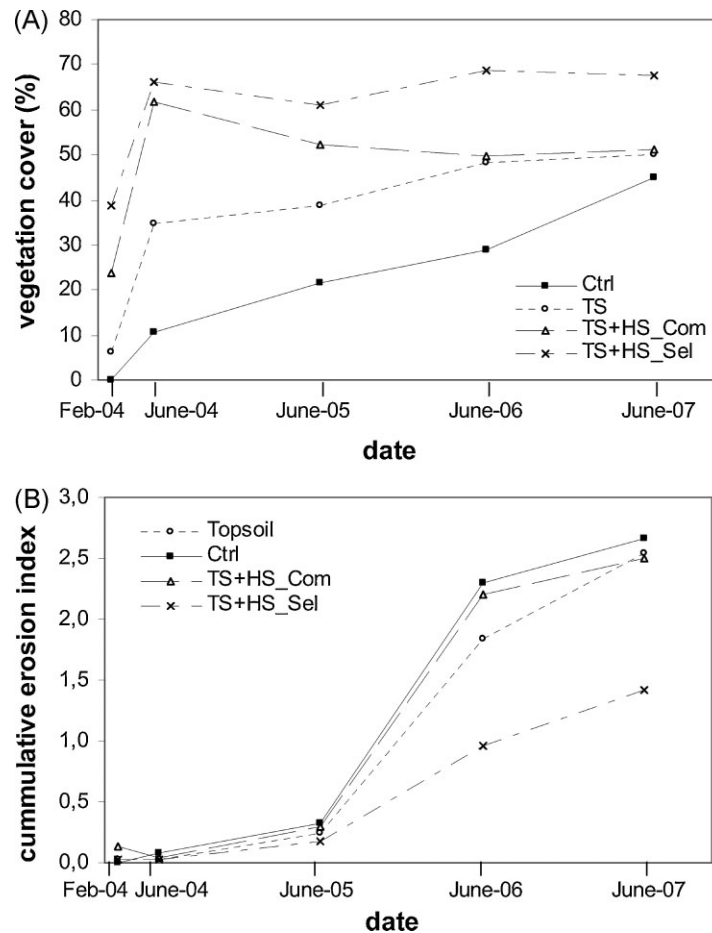


Figure 6. Total vegetation cover (per cent, mean \pm SE) and cumulative erosion index (mean \pm SE) for the four treatments on roadslopes through the study period. Treatments: Ctrl = no-topsoil and no-hydroseeding; TS = topsoil; TS + HS_Com = topsoil + hydroseeding with a standard seed mixture of commercial species usually used in semiarid Spain; TS + HS_Sel = topsoil + hydroseeding with a seed mixture of successful native species. Hydroseeding was performed at the end of October 2003.

Hydroseeding after topsoiling. Total vegetation cover was higher in the TS + HS_Com than in TS plots up to June 2005, but these differences disappeared in 2006 and 2007 as total cover in the hydroseeded TS + HS_Com plots decreased after the first growing season on ($F_{4,36} = 7.63$, $p < 0.01$ for the interaction, Figure 6A). Cumulative erosion in the TS + HS_Com plots was similar to that observed in the TS plots through the study period ($F_{1,9} = 0.32$, $p = 0.58$ for treatment; $F_{4,36} = 111.35$, $p < 0.001$ for time and $F_{4,36} = 0.52$, $p = 0.57$ for the interaction, Figure 6B).

On the contrary, the vegetation cover was significantly different in the hydroseeded plots with the selected seed mixture (TS + HS_Sel) and in the un-hydroseeded TS plot ($F_{1,10} = 14.31$, $p < 0.01$ for treatment). The TS + HS_Sel treatment provided relatively dense vegetation cover from the very first visits until the end of the study period (40 per cent 3 months after hydroseeding and > 60 per cent from that date on, $F_{4,40} = 4.45$, $p < 0.01$ for the interaction, Figure 6A.). The increase in erosion through time was significantly less pronounced in the TS + HS_Sel plots than in the TS ones ($F_{1,10} = 5.95$, $p < 0.05$), more specifically from June 2005 onwards ($F_{4,40} = 3.21$, $p < 0.05$ for the interaction, Figure 6).

Table IV. Index of hydroseeding success (per cent, mean \pm SE) for both hydroseeded seed mixtures through the study period

Hydroseeded seed mixture	Year of survey			
	2004	2005	2006	2007
ComMix (15 per cent <i>Lolium multiflorum</i> , 10 per cent <i>Vicia villosa</i> , 20 per cent <i>Festuca arundinacea</i> , 10 per cent <i>Medicago sativa</i> , 10 per cent <i>Onobrychis sativa</i> , 20 per cent <i>Agropyron cristatum</i> , 15 per cent <i>Melilotus officinalis</i>)	29.61 \pm 10.83	5.62 \pm 1.85	12.71 \pm 7.37	13.41 \pm 5.37
SelMix (21.2 per cent <i>Avena barbata</i> , 13.8 per cent <i>Bromus rubens</i> , 6.3 per cent <i>Anacyclus clavatus</i> , 5.1 per cent <i>Medicago minima</i> , 18.4 per cent <i>Diplotaxis erucoides</i> , 5.2 per cent <i>Plantago albicans</i> , 1 per cent <i>Medicago sativa</i> , 20 per cent <i>Dactylis glomerata</i>)	91.18 \pm 5.77	75.69 \pm 6.40	65.07 \pm 8.22	89.89 \pm 6.60

Hydroseeding success index is defined as the ratio between the absolute cover of hydroseeded species and the total cover of species in the plot in percentage. Between brackets, the species composition and per cent seed weight of each seed mixture. ComMix is a standard commercial seed mixture and SelMix is a seed mixture that includes the selected native successful species on roadslopes.

Species selection for hydroseeding. The selected seed mixture provided higher vegetation cover than the commercial seed mixture through the study period, but differences were not statistically significant ($F_{1,9} = 1.51$, $p = 0.25$ for treatment, $F_{4,36} = 1.35$, $p = 0.28$ for the interaction, Figure 6A). However, the absolute cover of hydroseeded species was much higher in the TS + HS_Sel than in the TS + HS_Com plots. Consequently, the HSI was 3–14 times higher for selected species than for commercial ones (Table IV).

The significantly lower erosion index in the TS + HS_Sel plots compared to that of the TS + HS_Com plots recorded throughout the study period ($F_{1,9} = 6.07$, $p < 0.05$ for treatment; $F_{4,36} = 72.73$, $p < 0.001$ for time and $F_{4,36} = 1.86$, $p = 0.14$ for the interaction, Figure 6B) confirmed the results obtained when comparing TS with TS + HS_Com plots.

Drilling. Seedling establishment success and mortality differed greatly between both species ($U_{MW} = 3.0$ and $U_{MW} = 4.0$, respectively, $n = 8$, $p < 0.01$). Among the 39.0 per cent of *P. albicans* seedlings which germinated and developed in the drilled plots on roadcuts, one third survived 1 year after sowing (13.2 per cent). All of the 4.8 per cent seedlings of *S. chamaecyparissus* that were able to germinate in the drilled plots died one year after sowing (0 per cent survival).

DISCUSSION

The experimental approach described in this study provides evidence of how key ecological processes and plant attributes can be effectively used to save effort and money in roadslope restoration in semiarid Mediterranean conditions. First, we identified ecological factors and processes that control plant colonisation and erosion processes on roadslopes in order to identify and test, in a second step, potential restoration strategies.

The analysis of natural regeneration processes on 8-year-old slopes revealed that the slope angle and type play a relevant role in plant establishment and erosion severity on roadslopes. Our results clearly show that vegetation is almost absent from slopes of angles greater than 45 degrees. The high degree of erosion and the increasing importance of mass movement processes on these slopes, compared to gentler ones, can explain the scarcity of vegetation on these slopes. Moreover, if we consider the high probability of seed removal by runoff or gravity (Cerdá and García-Fayos, 1997; García-Fayos and Cerdà, 1997), hydroseeding is bound to fail on such steep slopes. Engineering measures, rather than ecological ones should be considered in such cases, with the only objective to stabilise the soil and ensure road security (e.g. geotextiles, ...).

The slope type and, to a lesser extent, the slope aspect, had a strong influence on plant establishment and erosion on slopes lower than 45 degrees. Lower vegetation cover, that never reached 10 per cent, and a higher degree of rill

and gully erosion were recorded on roadcuts. Natural colonisation was slow on all slope types, except for north-facing roadfills. Manual sowing experiments helped to identify the processes responsible for the filtering of species from the surrounding natural plant communities. Despite seed introduction, the poor colonisation success of unsuccessful colonisers suggested that post-introduction processes, such as seed germination and seedling establishment limitations, control plant colonisation on these slopes. These results support the idea that the availability of microsites with favourable soil conditions is more limiting to plant establishment in Mediterranean ecosystems than the availability of seeds (Rey and Alcántara, 2000; García, 2001).

Roadslopes presented hostile soil conditions for plant establishment in terms of fertility (organic matter, nitrogen and phosphorous contents), structure (soil compaction) and water availability (soil water potential and soil drying dynamics). Moreover, soil conditions were less favourable to plant colonisation and more favourable for soil erosion on roadcuts than on roadfills, specifically in terms of water availability and soil compaction. It has been argued that a high speed of germination is vital in arid and semi-arid environments in which water availability is low (Evans and Etherington, 1990; Jurado and Westoby, 1992). In our study, the pattern of seed germination in water stress conditions was consistent with species success on roadslopes. Successful species on roadslopes showed faster germination and higher germination rates than unsuccessful species and, in turn, successful species on roadcuts had a higher speed of germination and higher germination rates than species exclusively successful on roadfills. Plant establishment success was therefore dependent on the slope characteristics.

Soil compaction also proved to be limiting for plant establishment on roadcuts, as none of the successful colonisers tested were able to penetrate wax layers as compacted as roadcut soils. This confirms the importance of the availability of microsites on roadcuts or cracks, with softer soil surfaces, that allow root penetration. Cracks, soil depressions, stones and litter accumulation have been reported as favourable microsites for seed germination, root penetration and further plant establishment (Harper, 1977; Dexter, 1986).

As topsoiling is still a difficult and dangerous mechanical operation on most roadcuts, soil improvement in these slopes (with angles > 45 degrees) was tested by drilling and adding seeds to increase the availability of favourable microsites for seed trapping, seed germination and for the next steps of plant establishment. Drilling provided promising results, suggesting that future efforts should focus on the development of new engineering techniques able to modify the soil topography and increase the availability of favourable microsites for added seeds to germinate and establish successfully. Yadav *et al.* (2007) also reported the advantages of drilled compacted soils for the establishment and grain yield of crop stands of rice in semiarid India. However, species selection seems to be an important contributing factor, as seedling establishment success and survival of the two species tested in our study seemed to be related to the ability of the species to quickly germinate in a number of days lower than that of water availability on these slopes. Bochet *et al.* (2007) described that *S. chamaecyparissus* had a lower germination rate and needed more days than *P. albicans* to germinate in the water-stress conditions that prevail in roadcuts during the germination period (16.4 and 58.5 per cent germination rate and 8.2 and 5.0 days respectively for the two species).

In roadfills, the low vegetation cover in the untreated plots confirms that, without restoration measures, natural colonisation takes place slowly in semiarid conditions. Consequently, active restoration seems to be essential for the enhancement of a rapid plant establishment on semiarid roadslopes. Topsoil spreading enhanced plant establishment compared to control plots, especially from the first growing season onwards. Several studies report that topsoiling influences plant establishment by improving soil properties and providing seeds of native species present in the soil seed bank (i.e. Albaladejo *et al.*, 2000; Holmes, 2001). However, vegetation never reached the critical threshold of 50 per cent cover established for effective erosion control in semiarid environments (Gyssels *et al.*, 2005 and Calvo *et al.*, 1992) and no significant reduction of erosion could be attributed to topsoil spreading. Hydroseeding after topsoiling was necessary to reach a higher cover than the mentioned threshold, although the relatively high cover achieved in the TS + HS_Com plots mainly resulted from the germination of native species which benefitted from the amendment supply during hydroseeding (70–94 per cent cover proportion due to native species from the soil seed bank or from surrounding areas). Contrary to the TS + HS_Sel plots, total vegetation cover in the TS + HS_Com plots tended to decrease up to cover values similar to that found in TS and Ctrl plots, as the proportion of total cover due to commercial species decreased from 30 per cent in the first year to less than 15 per cent in subsequent years. Favourable initial conditions (amendments and a high spring precipitation of

235.5 mm in 2004, greater than the 104.3 mm average for the period of 1961–1990; Pérez, 1994) were followed by 2 years of severe drought in 2005 and 2006 (72.0 and 66.6 mm Spring precipitation, respectively). Matesanz *et al.* (2006) obtained similar results in a wetter region with hydroseeding rendering undistinguishable results in terms of vegetation cover from natural processes on topsoiled embankments and also with low hydroseeding success of commercial species. They concluded that there are situations dependent upon a number of environmental conditions involving climate, slope factors and soil properties in which the use of hydroseeding for revegetation is not needed. However, in our study, the selected seed mixture was more effective in controlling erosion, as it reduced the cumulated erosion index by one class level compared to the other treatments we tried. Thus, in semiarid Mediterranean conditions, where droughts are frequent, topsoiling and hydroseeding are both needed to quickly reach cover higher than 50 per cent, necessary for slope stabilisation of erosion sensitive slopes. As the effect of hydroseeding after topsoiling on erosion strongly depends on the selection of species in the seed mixture, the effectiveness of the treatment on erosion control will only be guaranteed if a suitable mixture of species, able to overcome the climatic and soil adversities of semiarid roadslopes, is chosen. Given that the estimated cost of relevant ecological advantages provided by the use of native species in hydroseeding is only twice that of commercial species (Bochet *et al.*, 2009), the use of native species should be encouraged in roadslope restoration projects. Erosion prevention and local diversity conservation are two of the ecological advantages considered.

Finally, since precipitation strongly influences plant establishment, results of this study are dependent on the climatic conditions prevailing during the study period. The autumnal precipitation was low in the first year after hydroseeding (lower than the average calculated on the basis of a 29 years period: 8 mm in November 2003 just after hydroseeding and 97 mm during the autumn 2004 versus an average of 48 and 138 mm, respectively for the period of 1961–1990; Pérez, 1994) and did not allow us to detect differences in erosion control between treatments in the first months after hydroseeding when the risk of erosion is extremely high. However, differences in erosion were detected in the subsequent years which registered higher autumnal precipitations than the average (155 and 149 mm respectively in 2006 and 2007). We presume that the occurrence of intense rainfall events in the first months after hydroseeding would have provided even more evidence of the effectiveness of the TS + HS_Sel treatment and would have further supported our conclusions. This presumption is based on the differences in vegetation cover of all four treatments in February and June 2004 and on the threshold of effective erosion control by vegetation described by Gyssels *et al.* (2005). Our experimental process would need, however, to be repeated over different years and conditions to yield more precise predictions about optimal methods to be used in roadslope restoration.

In conclusion, ecological knowledge on roadslope functioning provided evidence that the improvement of soil conditions is needed to enhance plant colonisation. Moreover, some species from the local flora, adapted to the harsh conditions of the roadslopes, are able to successfully colonise roadslopes and could be chosen for hydroseeding if topsoiling is not as effective as required for erosion control.

A new challenge consists of convincing institutions devoted to restoration that scientific knowledge is needed to guide restoration efforts in Mediterranean ecosystems. New ways should also be established to efficiently transfer scientific knowledge to the institutions concerned (restorers, policymakers and practitioners, ...).

ACKNOWLEDGEMENTS

This research was supported by the Ministerio de Ciencia y Tecnología (projects 1FD97-0551 and REN2001-2313 and Programa Ramón y Cajal) and Fundación Bancaja. The authors are grateful to Intersementes S.A. that provided us with seeds for the hydroseeding experiments and to José Antonio Bellido, Daniel Montesinos and Manuel Monsalve for their help in field work. The authors are also grateful to Chris Allen for English editing.

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