Factors Controlling Vegetation Establishment and Water Erosion on Motorway Slopes in Valencia, Spain

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Abstract

In semiarid Mediterranean areas, the widespread environmental impact caused by the construction of motorways, railways, and pipelines has created an increasing need for effective restoration. We examined the influence of slope characteristics on vegetation and water erosion on 71 motorway slopes in a semiarid Mediterranean region. Specifically, we studied the effect of slope angle, type (roadfill vs. roadcut) and aspect (north vs. south) on soil properties, vegetation cover, species richness, floristic composition, and water-caused erosion. Temporal dynamics of soil water content was monitored and related to the soil water potential in order to explain possible differences in vegetation cover between slope types. The main factors influencing vegetation on motorway slopes were the angle, type, and aspect of the slope. Vegetation was almost completely lacking on roadcuts with slopes greater than 45°. On gentler slopes, vegetation cover was 44–78% on roadfills but did not reach 10% on roadcuts, regardless of aspect. The main soil properties affected by the slope type and aspect were the organic matter content, soil available P, and water content. Rill erosion, gully erosion, and mass movement were all significantly higher on roadcuts than roadfills. A total of 308 spontaneous colonizers and seeded species were recorded. The type and aspect of the slope also controlled species composition. The short duration of available water in the soil with respect to soil water potential proved to be a limiting factor to plant colonization on roadcuts and south-facing slopes as well as the low soil fertility in the case of roadcuts. Our results underscore the difficulty of revegetating slopes with angles greater than 45°, where the probability of seeds moving downhill is high. Future efforts should focus on increasing the surface roughness or building terraces at regular intervals in order to reduce slope angle to less than 45° and favor seed trapping and germination. On gentler slopes, adjusting of seed mixes according to dominant species associated with each slope type and aspect should improve considerably the success of roadside revegetation.

Key words: erosion, motorway slopes, restoration, soil properties, soil water availability, vegetation.

Introduction

In the last decades the construction of linear infrastructures such as motorways, railways, and pipelines has been highly controversial because of their severe and wide impact on ecosystems. Apart from their direct effects, linear infrastructures fragment landscapes and may result in biodiversity loss (Navarro & Ugalde 1995; Whisenant 1999; Nicolau & Asensio 2000; Balaguer 2002). One of the main impacts of construction is the creation of bare, steep slopes that are exposed to the direct action of rainfall and high rates of water erosion. Thus, the widely accepted role of the vegetation in controlling soil loss and runoff (i.e., Elwell & Stocking 1976; Wischmeier & Smith 1978; Snelder & Bryan 1995) is also essential in the stabilization of motorway slopes (Larrea & Arnáez 1994; Andrés & Jorba 2000). Vegetation reduces water-caused erosion by intercepting rainfall (Tromble 1987; Cabezas et al. 1991), increasing water infiltration on associated "soil-fertility" islands (Cerdà 1995; Bochet et al. 1999), intercepting runoff at surface level (Sánchez & Puigdefábregas 1994; Bochet et al. 2000), and stabilizing soil with roots.

In semiarid environments, high rainfall variability makes restoration especially challenging (Aronson et al. 1993; Le Houérou 2000). One of the main practices to reclaim motorway slopes is hydroseeding, that is, spraying a mixture of water, seeds, fertilizers, fixing substances, and mulches. A mixture of herbaceous species (mainly grasses and legumes) that quickly produces a dense cover is usually used. In semiarid Mediterranean Europe, however, long periods of drought and intense rainfall frequently cause hydroseeding to fail (Bautista et al. 1997; Andrés & Jorba 2000). One cause for this is sowing commercial species usually used for restoration in central Europe, but which are unsuitable in Mediterranean systems. Other causes of failure in our region include seed removal by water running over bare and crusted soils, high rates of plant mortality due to recurrent drought, and an inability of some species to expand their populations in dry conditions (Mitchley et al. 1996; Cerdà & García-Fayos 1997;

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García-Fayos & Cerdà 1997). In addition to hydroseeding, rooted shrubs are commonly transplanted for motorway slope restoration, but the results obtained are also poor because of the inability of transplants to capture water and nutrients in soils without organic matter (Paschke et al. 2000). Alternative solutions based on bioengineering techniques are sometimes adopted to improve the efficiency of hydroseeding and transplanting, such as the use of synthetic grid-like materials to stabilize soil. However, these measures greatly increase the cost of revegetation (Cotts et al. 1991; Barker 1996; Paschke et al. 2000). An alternative to hydroseeded species is to explore the ability of native plants to colonize spontaneously the bare slopes with the final objective of restoring the original habitat and preserving regional biodiversity. Before this becomes possible, information on the factors that influence plant colonization on motorway slopes is needed.

Our goals were to determine the slope characteristics that control vegetation establishment and water erosion on motorway slopes. We hypothesized that:

(1) Slope angle limits the establishment of the vegetation, in terms of vegetation cover and species richness.
(2) Slope type and aspect influence the amount and composition of the vegetation as well as the prevalence of the different water erosion processes through the control of soil characteristics and soil moisture dynamics.

Methods

Description of the Study Area

The study area is located in the region called "La Plana de Utiel-Requena" of the Valencian Community, Spain (39°29′N; 1°06′W). The motorway slopes selected for the study were at 267–307 km of the A-3 dual carriageway that links Valencia and Madrid.

The geology, climate, and slope age were homogeneous along the selected road section. The construction of the road and adjacent slopes on calcareous marls and clays of Tertiary origin (García 1996) was completed between winter 1992 and summer 1994. All motorway slopes were hydroseeded just after the road was built with a mixture of legumes and grasses (see Appendix 1). Mean annual precipitation and temperature at Requena are 418 mm and 14.2 °C, respectively (Pérez 1994). Rainfall distribution between and within years is very variable showing two peaks in May and October. The large temperature range gives a continental aspect to this area where frost events occur in winter and droughts are associated with the summer period.

The actual vegetation that borders the road results from human activities carried on in this region for centuries. Most of the surrounding areas are currently cultivated (mainly vineyards, but also almond and olive orchards), but there are small patches of shrublands and open forests where *Pinus halepensis* (Pinaceae) is the most abundant tree, *Rosmarinus officinalis* (Lamiaceae), *Thymus vulgaris* (Lamiaceae), *Genista scorpius* (Fabaceae), and *Quercus coccifera* (Fagaceae) are the dominant shrubs, and *Brachypodium retusum* (Poaceae), *Koeleria vallesiana* (Poaceae), *Stipa offneri* (Poaceae), and *Helictotrichon filifolium* (Poaceae) are the dominant grasses.

Motorway Slope Selection

Study slopes selected were all greater than 20 m long, 5 m high, and 25° steep and had less than 5% cover of rock outcrops. Sampling accounted for the type, aspect, and angle of slopes. There were two types of motorway slopes, roadcuts resulting from the excavation of high areas and roadfills, which were built by accumulating and compacting unconsolidated materials from an adjacent area. As the A3-motorway runs east to west, the resulting slopes are oriented north or south.

We sampled 71 motorway slopes in 2000, including 45 roadcuts and 26 roadfills, both groups including north- and south-oriented slopes. Whereas all the roadfills had slope angles less than 45°, two main groups of roadcuts were considered according to their inclination: a first group of 21 roadcuts with slopes less than 45° situated along the road and a second group of 24 roadcuts with slopes greater than 45° beside exit roundabouts. The effect of slope angle on plant establishment was determined, considering these two homogeneous groups of roadcuts of the same origin (both excavated) that differed only in their inclination. The influence of soil characteristics and other slope factors (slope type and aspect) was determined, taking only into account a more homogeneous set of slopes all under 45 ° (roadcuts and roadfills) (Table 1). Slopes greater than 45 ° were not included in this second analysis, not only because they were restricted to exit roundabouts and represented a small proportion of the area occupied by the road slope

Table 1. Site characteristics of the 47 sampled motorway slopes (<45°) (mean values ± SE).

	Roadcuts		*Roadfills*	
	North (n = 10)	*South (n = 11)*	*North (n = 12)*	*South (n = 14)*
Slope angle (°)	36.3 ± 0.8	35.9 ± 0.8	32.2 ± 0.8	31.2 ± 0.5
Height (m)	9.4 ± 1.4	9.8 ± 1.2	10.8 ± 0.9	12.8 ± 1.3
Area (m^2)	1276.3 ± 495.8	1600.1 ± 698.5	1272.7 ± 367.7	1267.8 ± 316.0

network (<10%) but also because the very strong influence of their inclination on plant establishment might obscure the more subtle effects of soil parameters.

Vegetation Parameters

The success of plant colonization was expressed in terms of total vegetation cover, floristic composition, and species richness.

Total cover was visually estimated by two observers 20 m from the slope. In all cases the two observers were the same. The sampling area was divided into adjacent 5-m-wide vertical strips, and the maximum acceptable difference in cover estimation for any strip between the two observers was 10% (otherwise the estimate was repeated). Total cover for the whole sampled area was calculated as the mean of all strip covers. Floristic composition was determined by two persons who walked the sample area in two lines parallel to the road, one in the upper part and the other in the lower part of the slope, and noted all species found in their respective fields of vision. A first survey was performed at the beginning of the spring and a second at the beginning of the summer in order to include as many species with different phenologies as possible.

The sampling area was proportional to the size of the road slopes and ranged from 150 to 8,000 m^2. Although the size of the sampling area was different in all cases and might affect species richness, its distribution was homogeneous between all the sets of slopes considered in the analyses. The similarity of distributions of the size of sampled areas was statistically confirmed between roadcuts less than 45° and greater than 45° ($U_{MW} = 179.5$; $p = 0.099$), between roadfills and roadcuts less than 45° ($U_{MW} = 239.5$; $p = 0.612$), and between north- and south-facing slopes ($U_{MW} = 226.0$; $p = 0.421$). Species richness was standardized to a unit area (number of species in 100 m^2).

Water Erosion Processes

The severity of water erosion on slopes was determined by considering rill erosion, gully erosion, and mass movement separately. Classes from 0 to 3 were defined according to the percentage cover of rills, gullies, and mass movements, respectively, within the same vertical strips as for the vegetation cover estimations (0: no erosion, 1: % cover $\leqslant 1/3$, 2: % cover between 1/3 and 2/3, and 3: % cover $> 2/3$ of the total sampling area). The final value of each subprocess for a given slope was calculated as the mean of all partial estimates given by the two observers to the successive strips. An overall index of water erosion was also assigned to each slope and defined as the sum of the values obtained for the three subprocesses (González del Tánago 1993; Guerrero 1998).

Soil Characteristics

Two soil samples (10 cm deep) were collected from each slope. Soil texture (percent sand, silt, and clay content), stable aggregates, and chemical characteristics (organic matter, total nitrogen, and available phosphorus) were determined. Particle-size distribution (<2 mm) was determined by the hydrometer method (Gee & Bauder 1986). Stable aggregates were determined by the wet sieving method described by Primo & Carrasco (1973). Analyses of the soil chemical properties were performed using the procedures of Page et al. (1982): the Walkley–Black method for organic matter, the Kjeldahl method for total nitrogen, and the Olsen method for available phosphorus. Richard's standard pressure chamber (Klute 1986) was used to determine soil moisture content at wilting point (1,500 KPa), expressed as the volumetric soil moisture content (cm^3 water/cm^3 soil). We assume that soil moisture available for plant functions (germination and development) was that retained in the soil above the wilting point.

Soil Moisture Dynamics

In order to characterize soil moisture dynamics, soil was sampled (5 cm deep and 5.5 cm diameter) from October 2000 to June 2001 in two areas of each slope after an abundant rainfall event. Soil moisture content was measured daily during the first week after the rainfall and then more irregularly until the dry summer period. Soil water content was determined gravimetrically.

Statistical Analyses

The influence of slope angle on vegetation cover and species richness was determined using Mann–Whitney U tests, because data could not be normalized. The effects of aspect and type of motorway slopes on vegetation cover, species richness, and soil physical and chemical properties were determined using two-factor ANOVA, after transforming variables to fit the assumptions of normality and homogeneity of variances. Nonparametric correlations were used to determine the relationship between erosion processes and vegetation parameters.

Correspondence analysis was used to determine the dependence of the floristic composition on the aspect and type of slope. This analysis was performed with common species present on more than 10% of the slopes (Causton 1988).

SPSS statistical package version 11.0 was used for two-factor ANOVA models and correlations, and the NTSYSpc 2.02 statistical package was run for correspondence analyses.

Results

Influence of the Slope Angle on Vegetation Establishment

Plant colonization on roadcuts greater than 45° was almost nonexistent, with mean values of vegetation cover of $1.6 \pm 0.5\%$ (mean ± SE) significantly less than on roadcuts less than 45° ($7.4 \pm 1.2\%$) ($U_{MW} = 58.5$, $p < 0.001$). Species richness was also significantly lower on roadcuts greater than 45 ° (3 species ± 1) than on slopes less than 45 ° (10 species ± 2; $U_{MW} = 132.0$, $p = 0.006$).

Influence of Slope Type and Aspect on Vegetation, Soil, and Erosion (Only Slopes <45°)

Vegetation Parameters. The aspect and type of motorway slopes (<45 °) both had a strong influence on vegetation cover (Fig. 1a). p values for type and aspect were less than 0.001 and $p = 0.002$ for their interaction ($F_{1,43}$). Roadfills had significantly higher cover than roadcuts (59.4 ± 4.7% and 7.4 ± 1.2%, respectively, averaged across slope exposure), and north-facing slopes were significantly more vegetated than south-facing ones (47.0 ± 7.8% and 26.7 ± 4.8%, respectively, averaged across slope type). Furthermore, the influence of slope aspect on cover differed between slope types (see high significance of the interaction). Whereas the difference in cover between north- and south-oriented roadfills was great, the differences were small between the north- and south-facing slopes of roadcuts (Fig. 1a).

Species richness did not vary significantly with slope type or aspect ($p = 0.478$ for type, $p = 0.385$ for aspect, and $p = 0.584$ for their interaction) (Fig. 1b).

We found 308 plant species, with 122 species present in more than 10% of the slopes including 12 hydroseeded and 110 naturally establishing species (Appendix 2). The two first dimensions of the correspondence analysis explained only a small portion of the variability of the whole set of slopes (10.6 and 7.4%, respectively). However, the segregation of motorway slopes by these two dimensions suggests that the slope type and aspect influence the floristic composition of the motorway slopes. Coordinates on dimension 1 are significantly lower for roadfills than for roadcuts ($U_{MW} = 61.0$, $p < 0.001$), and coordinates on dimension 2 are significantly lower for north-oriented slopes than for south-oriented ones ($U_{MW} = 116.0$, $p = 0.001$) (Fig. 2). In a second step the same analysis was performed with the 110 native species excluding the commercial hydroseeded species from the list. The results obtained were very similar, indicating that the type and aspect of the slope influenced the selection of naturally establishing species that colonized the motorway slopes from the adjacent areas.

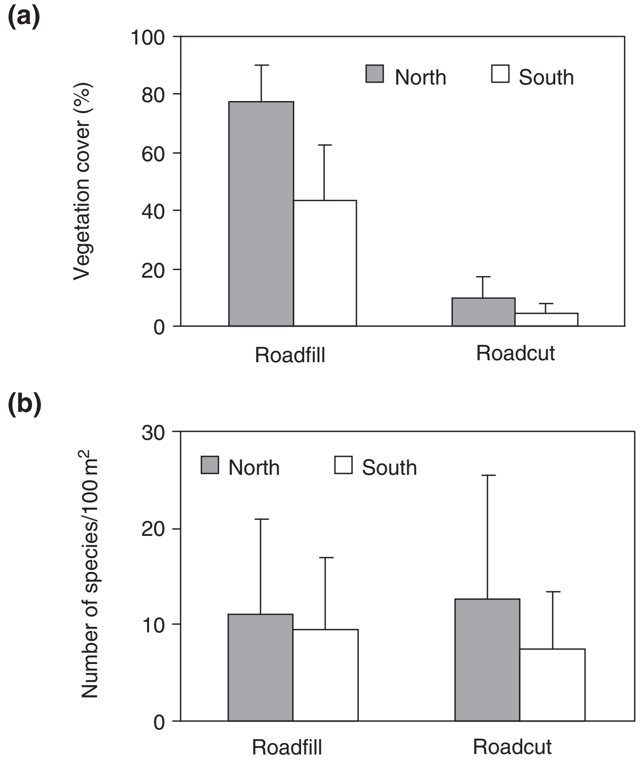

Figure 1. Mean vegetation cover (a) and species number/100 m^2 (b) with their respective SD of north- and south-facing slopes of roadfills and roadcuts (<45°).

Dominant species were the hydroseeded perennial legumes *Medicago sativa* and *Onobrychis viciifolia*, which together covered more than 50 and 20% of north- and south-oriented roadfill slopes, respectively, and less than 10 and 5% of north- and south-exposed roadcut slopes, respectively. Among the naturally establishing species, *Avena barbata*, *Bromus rubens*, *Hordeum murinum* (Poaceae), *Diplotaxis erucoides*, *Alyssum simplex* (Brassicaceae), *Anacyclus clavatus*, and *Sonchus oleraceus* (Asteraceae) were the most important species on all slope types and aspects. Other successful annual species were associated with a specific slope type or aspect, such as the abundant *Calendula arvensis* (Asteraceae) or *Medicago minima* (Fabaceae) on roadfills, *Eryngium campestre* (Apiaceae) on roadcuts, *Scorzonera laciniata* (Asteraceae) or *Silene nocturna* (Brassicaceae) on north-facing slopes, or *Plantago albicans* (Plantaginaceae) or *Pallenis spinosa* (Asteraceae) on south-facing slopes.

Water Erosion. The type of slope had a strong influence on most erosion subprocesses as well as on the overall erosion index (Fig. 3a). Erosion was significantly greater on roadcuts

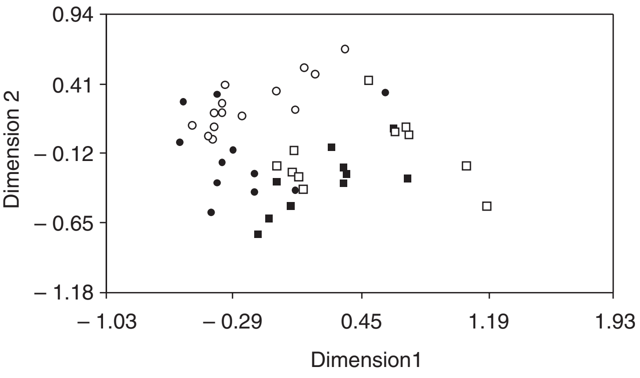

Figure 2. Results of correspondence analysis, where 46 motorway slopes (<45°) have been spatially plotted in accordance with their floristic composition, including hydroseeded species. ●, north roadfill; ○, south roadfill; ■, north roadcut; □, south roadcut.

than roadfills ($U_{MW(rills)} = 60.5$, $p < 0.001$; $U_{MW(gullies)} = 162.5$, $p = 0.017$; $U_{MW(mass\ movement)} = 221.5$, $p = 0.109$; $U_{MW(overall\ erosion)} = 75.0$, $p < 0.001$). However, no clear effect of slope aspect on erosion was observable (Fig. 3b).

Vegetation cover was negatively and significantly correlated with all erosion subprocesses and the overall erosion index ($r_{(rills)} = -0.736$; $r_{(gullies)} = -0.329$; $r_{(mass\ movement)} = -0.315$; $r_{(overall\ erosion)} = -0.675$; $p < 0.001$, $n = 47$ in all cases). Total erosion was significantly and negatively correlated with species richness ($r = -0.364$, $n = 46, p = 0.013$).

Soil Characteristics and Soil Moisture Dynamics. Soil organic matter ($F_{1,4} = 87.4$, $p = 0.001$) and available phosphorus ($F_{1,4} = 10.7$, $p = 0.031$) were significantly higher in roadfills than in roadcuts. The same trend was found for total nitrogen, although it was not significant ($F_{1,4} = 4.9$, $p = 0.09$) (Table 2). No soil variable was influenced by slope aspect or any interaction.

Soil moisture at wilting point was lower on roadfills ($0.136 \pm 0.008\,cm^3$ water/cm^3 soil, $n = 4$) than on roadcuts ($0.170 \pm 0.004\,cm^3$water/cm^3 soil, $n = 4$; $t = -4.1$, $df = 6$, $p = 0.006$), indicating higher water-holding capacity in roadfills than in roadcuts.

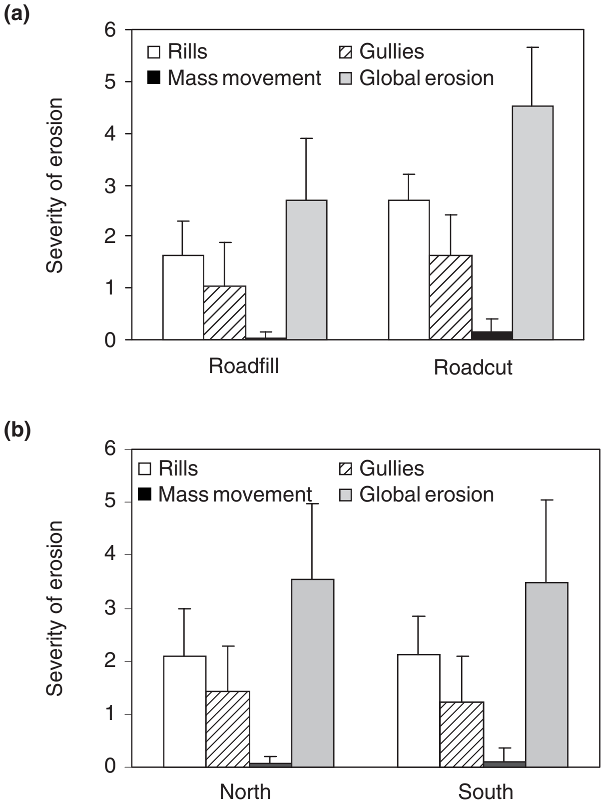

Figure 3. Intensity of water erosion subprocesses and total erosion according to the type (a) and aspect (b) of the slopes (<45°). The mean values for each process were all significantly different (except for mass movement) between roadfills and roadcuts using a Tukey's Studentized range test ($p = 0.05$), whereas no significant differences were detected between north and south aspects.

After a high rainfall event between 20 October 2000 and 25 October 2000, soil moisture content stayed above the wilting point for only 8, 9, and 15 days in the south-facing roadcuts, south-facing roadfills, and north-facing roadcuts, respectively, but until the next summer (June) in the case of north-oriented roadfills.

Discussion

In general terms, slope angle, type, and aspect all greatly influenced vegetation establishment and composition of the motorway slopes.

The very low plant cover characteristic of the steepest roadcuts with slope angles greater than 45° underscores the difficulty of revegetating these extreme slopes. Andrés et al. (1996) obtained similar results on the slopes of a motorway in Catalonia (Spain), with somewhat higher total covers on an irregular, soft, and weathered surface material and concluded that hydroseeding was not appropriate for slope stabilization of roadcuts near or above 45°. The causes of failure include the probability of seeds moving downhill, with or without water (Cerdà & García-Fayos 1997; García-Fayos & Cerdà 1997). Thus, future efforts should focus on increasing the surface roughness of the slope, building terraces at regular intervals, or excavating to produce slope angles well under 45°.

On gentler slopes (<45°), roadfills were better for plant establishment than roadcuts. The scarceness of the vegetation on roadcut slopes (<45°) could be an indicator of environmental harshness or of the impossibility of seeds to stay on these bare crusted slopes. The chemical and hydrological status of these slopes indicated a very low fertility (low phosphorus, nitrogen, and organic matter content) as well as a high restriction of available water for plants. Differences in vegetation cover between forest motorway slope types in La Rioja (Spain) were also described by Larrea and Arnáez (1994) with denser mean covers on roadfills (20–25%) than on roadcuts (1–5%).

The well-known influence of aspect on plant colonization and recovery was also evident, with north-facing vegetation covers being almost two times denser than south-facing ones and differing in the floristic composition.

The severity of water erosion, determined by the slope type, seemed to be a hindrance to plant establishment and survival on motorway slopes less than 45°, especially on roadcuts. According to Andrés and Jorba (2000), erosion rates are severe and unacceptable unless vegetation cover exceeds 50% of the motorway slope area. Consequently, the only motorway slopes that could prevent erosion in our study area would be the north-oriented roadfills.

Unlike other studies based on quantitative estimations of erosion on motorway slopes (i.e., Arnáez & Larrea 1995; Andrés & Jorba 2000), we found no effect of aspect on the intensity of erosion. This could be a consequence of

Table 2. Soil characteristics of north- and south-oriented roadfills and roadcuts (<45°).

	Roadcuts		*Roadfills*	
	North	*South*	*North*	*South*
Sand (%)	40.84 ± 11.52	32.06 ± 0.87	35.10 ± 2.67	41.14 ± 7.63
Lime (%)	32.66 ± 6.64	35.80 ± 2.53	30.73 ± 2.07	24.23 ± 3.52
Clay (%)	26.56 ± 4.94	32.14 ± 1.67	34.18 ± 0.60	37.89 ± 14.31
Stable aggregates (%)	22.82 ± 6.69	37.52 ± 3.64	31.23 ± 7.16	30.82 ± 2.07
O.M. (%)	<0.8*	<0.8*	1.2 ± 0.0	1.5 ± 0.2
N_{total} (%)	<0.070*	<0.070*	<0.070*	0.076 ± 0.002
$P_{available}$ ($mg\ P_2O_5\ 100\ g\ soil^{-1}$)	0.5 ± 0.1	0.5 ± 0.1	1.9 ± 0.9	3.1 ± 1.4

Values are mean ± SE ($n = 2$ in all cases).
*Lower than the level of detection of the method used.

the semiquantitative methodology used here, which may not have been precise enough to detect such differences.

The soil fertility as well as the available water usable by plants and its temporal variation after a rainfall event seemed to be some of the main factors responsible for the differences in vegetation cover observed between the different motorway slopes (<45°). Soil fertility was lower in roadcuts than in roadfills as expressed by the organic matter, available phosphorus, and total nitrogen contents. Moreover, in all south-facing slopes and north-facing roadcuts, the soil dried more quickly than it did on north-facing roadfills, reaching the wilting point more quickly after a rainfall. North-facing roadfills behaved similarly to a surrounding matorral reference site (typical Mediterranean shrubland vegetation) where the water remained available in the soil for the plants till the very warm and dry summer season (Bochet & García-Fayos, unpublished data). The effect of aspect on the dynamics of water availability seemed to be more important than the effect of the soil structure and texture, because the south-facing slopes reached the wilting point more quickly than the north-oriented slopes. This could be due to the lack of insolation on the north-facing slopes in winter, whereas in the same period, south-facing slopes do receive insolation. García-Fayos et al. (2000) stated that the main factor limiting plant colonization on badland slopes in southeastern Spain on materials of the same tertiary origin as our study site was the very short duration of available water in the soil due to the physical and chemical characteristics of the regolith (high salinity and clay content). These authors concluded that regolith water availability had detrimental effects on seed germination, as the soil moisture stayed above the wilting point for 1–7 days after the rainfall ceased and the time needed for seed germination was longer. Thus, the dynamics of soil water availability and the different efficiency in water use between plant species could also explain the differences in plant composition observed in our study between the slope types and aspects.

In conclusion, hydroseeding is unsuitable for stabilizing steep (>45°) slopes, because the probability of seeds moving downhill is high. Future efforts should focus on increasing the surface roughness or building terraces in order to reduce the slope angle to less than 45° in order to favor seed trapping and germination. On gentler slopes, north-facing roadfills reach an acceptable vegetation cover, able to reduce significantly water erosion with the commercial hydroseeded mixtures. On roadcuts (<45°) and south-facing slopes, however, revegetation success by hydroseeding is still unsatisfactory. The different ecological constraints (i.e., soil fertility, available water content, and temporal variation) of each slope type and aspect should dictate the selection of species to be included in the seed mixes in order to improve revegetation success on these slopes. Thus, besides the hydroseeded perennial legumes *Medicago sativa* and *Onobrychis viciifolia* that are successful on all types of slopes (<45°), other naturally establishing species such as *Avena barbata*, *Bromus rubens*, *Hordeum murinum*, *Diplotaxis erucoides*, *Alyssum simplex*, *Anacyclus clavatus*, and *Sonchus oleraceus* could be included in the seed mixes of all kind of slopes (<45°). More specifically, the inclusion of specific annual colonizer species in seed mixes specific to each slope type and aspect could be an alternative strategy in roadside vegetation (i.e., *Calendula arvensis* or *Medicago minima* on roadfills, *Eryngium campestre* on roadcuts, *Scorzonera laciniata* or *Silene nocturna* on north-facing slopes, or *Plantago albicans* or *Pallenis spinosa* on south-facing slopes).

Acknowledgments

We thank UE-FEDER and the Spanish “Plan Nacional de I + D + I del Ministerio de Ciencia y Tecnología” (projects 1FD97-0551 and REN2001-2313) for funding, D. Montesinos for field assistance, the staff of the laboratories of the CIDE for soil analyses, the Department “Demarcación de Carreteras del Estado en Valencia del Ministerio de Fomento” for data on motorway slope building and hydroseeding treatments, and S. Wilson and two anonymous referees for comments on the manuscript.

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Appendix 1. The species composition of seed mixtures used for motorway slope hydroseeding. Seeds (30 g/m^2) were hydroseeded in combination with a mixture of fiber mulch (150 g/m^2), fertilizers (100 g/m^2 organic fertilizer and 50 g/m^2 mineral fertilizer N-P-K), algin-based binding substances (4 g/m^2), and hydrocolloid- and anionic water-soluble polymer-based fix substances (20 g/m^2).

Family and species name	*% of seed mixture*
Poaceae	
Bromus inermis	10
Festuca rubra	15
Cynodon dactylon	5
Lolium multiflorum	10
Puccinellia distans	2
Festuca arundinaceae	17
Eragrostis curvula	5
Fabaceae	
Medicago sativa	7
Vicia villosa	6
Trifolium repens	6
Onobrychis viciifolia	11
Trifolium campestre	6

Appendix 2. List of hydroseeded (in bold) and naturally occurring species found by the authors in more than 10% of the motorway slopes studied.

Alliaceae
- *Allium porrum*

Apiaceae
- *Daucus carota*
- *Eryngium campestre*
- *Foeniculum vulgare ssp. piperitum*

Asphodelaceae
- *Asphodelus fistulosus*

Asteraceae
- *Anacyclus clavatus*
- *Atractylis humilis*
- *Calendula arvensis*
- *Carduus pycnocephalus*
- *Carduus tenuiflorus*
- *Carthamus lanatus*
- *Catananche caerulea*
- *Centaurea aspera*
- *Centaurea melitensis*
- *Chondrilla juncea*
- *Cichorium intybus*
- *Crepis foetida*
- *Crepis vesicaria*
- *Filago pyramidata*
- *Galactites duriaei*
- *Galactites tomentosa*
- *Hedypnois cretica*
- *Helichrysum serotinum*
- *Helichrysum stoechas*
- *Inula viscosa*
- *Lactuca serriola*
- *Launaea fragilis*
- *Launaea pumila*
- *Leontodon longirrostris*
- *Pallenis spinosa*
- *Pilosella anchusoides*
- *Santolina chamaecyparissus ssp. squarrosa*
- *Scolymus hispanicus*
- *Scorzonera angustifolia*
- *Scorzonera laciniata*
- *Senecio gallicus*
- *Senecio vulgaris*
- *Silybum marianum*
- *Sonchus oleraceus*
- *Sonchus tenerrimus*
- *Tragopogon dubius*

Boraginaceae
- *Anchusa arvensis*
- *Echium vulgare*

Brassicaceae
- *Alyssum simplex*
- *Cardaria draba*
- *Diplotaxis erucoides*
- *Hirschfeldia incana*
- *Matthiola fruticulosa*
- *Rapistrum rugosum*
- *Sisymbrium irio*
- *Sisymbrium orientale*

Caryophyllaceae
- *Cerastium pumilum*
- *Paronychia aretioides*
- *Petrorhagia prolifera*
- *Silene colorata*
- *Silene nocturna*
- *Silene vulgaris*

Cistaceae
- *Helianthemum violaceum*

Convolvulaceae
- *Convolvulus arvensis*

Dipsacaceae
- *Scabiosa atropurpurea*
- *Euphorbia helioscopia*
- *Scabiosa simplex*

Euphoriaceae
- *Euphorbia serrata*
- *Mercurialis tomentosa*

Fabaceae
- *Astragalus hamosus*
- *Coronilla scorpioides*
- *Genista scorpius*
- *Hippocrepis scorpioides*
- ***Lotus corniculatus***
- *Medicago doliata*
- *Medicago littoralis*
- *Medicago minima*
- ***Medicago sativa***
- ***Melilotus officinalis***
- *Melilotus sulcata*
- ***Onobrychis viciifolia***
- *Ononis pusilla*
- *Scorpiurus muricatus*
- *Trigonella polyceratia*
- *Ulex parviflorus*
- *Vicia peregrina*

Geraniaceae
- *Erodium ciconium*
- *Erodium cicutarium*
- *Erodium malacoides*

Hyacinthaceae
- *Muscari neglectum*

Lamiaceae
- *Marrubium supinum*
- *Rosmarinus officinalis*
- *Salvia verbenaca*
- *Thymus vulgaris*

Malvaceae
- *Althaea hirsuta*
- *Malva neglecta*

Papaveraceae
- *Glaucium corniculatum*
- *Papaver rhoeas*

- Plantaginaceae
  - *Plantago albicans*
  - *Plantago coronopus*
  - *Plantago lanceolata*
  - *Plantago sempervirens*
- Poaceae
  - *Aegilops geniculata*
  - *Aegilops triuncialis*
  - *Avenula bromoides*
  - ***Agropyron pectinatum***
  - *Avena barbata*
  - *Avena sterilis*
  - *Brachypodium retusum*
  - ***Bromus inermis***
  - *Bromus rubens*
  - *Bromus tectorum*
  - ***Cynodon dactylon***
  - ***Dactylis glomerata***
  - ***Elymus repens***
  - ***Festuca valentina***
  - *Hordeum murinum ssp. leporinum*
  - *Koeleria vallesiana*
  - ***Lolium rigidum***
  - *Piptatherum miliaceum*
  - *Stipa offneri*
- Polygonaceae
  - *Rumex pulcher ssp. woodsii*
- Resedaceae
  - *Reseda phyteuma*
  - *Reseda undata*
- Rosaceae
  - ***Sanguisorba minor***
- Rubiaceae
  - *Asperula aristata*
- Scrophulariaceae
  - *Linaria simplex*