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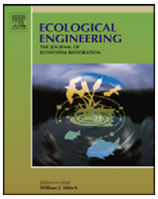

Opencast mine restoration in a Mediterranean semi-arid environment: Failure of some common practices

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ABSTRACT

Restoration works in opencast mining are mostly done with fast-growing herbaceous species to control the erosion of embankments during rainfall, especially immediately after their construction. Such species often exhibit a high demand for water and their survival is therefore associated to an adequate hydric supply. If this fails, these species can rapidly disappear when water is scarce. This paper shows the results of a restoration experiment where two stony mineral substrates were used in a quarry area (NE Spain). The experiment was carried out at lysimeter scale and the aim was to evaluate the short time vegetation response to common restoration practices in semiarid areas with two types of substrates and two types of irrigation practices. Lysimeter results were used to indirectly draw implications for the usual irrigation practices in the area.

During periods of the first year after sowing, irrigated and non-irrigated lysimeters were monitored for substrate humidity, water leachates and plant development. The population cover of sown plants fluctuated according to the water availability in the substrate before drought. Density of total basal shoots decreased dramatically during the period of water stress, reaching negligible cover values on both types of substrates.

Water content in the top substrate (0–20 cm) was dramatically reduced in June, just after the maximum plant cover and water demand were reached (May).

According with our results, it is not advisable to aim at a continuous and dense herbaceous cover composed of species that are not drought tolerant in restoration works, especially if embankments are constructed with spoil mine substrates. The restoration of opencast areas should include the use of water stress-resistant plants and careful irrigation plans.

1. Introduction

Quarry exploitation causes significant environmental problems as a consequence of soil removal and drastic changes in the original drainage network and topography (Clemente et al., 2004; Bradshaw and Chadwick, 1980).

The Spanish environmental authorities require the deposit of financial guarantees to ensure that restoration takes place once the extraction is finished. After a satisfactory restoration of the site (security, morphological adaptation, and vegetation), that deposit is released (Ministerio de la Presidencia, 2009). This encourages companies to complete the restoration works and to implement adequate vegetation covers. Sustainability, improved management of rainwater and reduction of visual impact are the main goals of any restoration plan necessary to recover the deposited bonds. In the mid-term, the restoration should also promote the development of diversity and functioning traits similar to those of the reference environment (Hooper et al., 2005; Jorba and Vallejo, 2008).

Vegetation is introduced on the embankments to reduce their erosion, but the physical conditions of the overburden materials (usually amended with organic waste) used as substrates are often unfavourable for plant growth: they are bare, have inadequate particle size distribution and high contents of gravel, and are frequently shallow (Bradshaw and Chadwick, 1980). Runoff water and drainage are fast and substrate usually remains very dry. The development of an herbaceous cover is constrained by water shortage (Barker and Caradus, 2001) and, consequently, restoration of limestone quarries in semiarid climates should firstly settle how water will be managed.

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Very dry summers (common in Mediterranean areas) and constraints in soil water availability are two relevant factors for biodiversity (Duckworth et al., 2010). This relationship has been widely described in the literature, especially for semi-arid ecosystems: seedling survival and development depend on soil water availability (Bertiller et al., 1996; Gonzalez-Dugo et al., 2005). In tall fescue, the weight of tillers decreases with decreasing soil water content (Bartholomew and Williams, 2006); available soil moisture determines tiller population growth or leaf area (McCarty, 1991; White, 1992; Ervin, 1998; Assuero et al., 2002).

Although plants used for restoration projects should be chosen from among the local vegetation (better adapted to local conditions and to cope with drought, Khater et al., 2009), some non-native species of high growth potential are generally used to control erosion. Perennial forages tend to use water more efficiently than annuals because their regrowth is faster after earlier autumn rains and they take better advantage of the residual deep moisture in late spring (Annicchiarico et al., 2011). However, sowings of embankments often include species of rapid growth such as raygrass, orchardgrass, and tall fescue (Albaladejo et al., 2000; Tormo et al., 2007) which are quite water-demanding. For example, values of ETr (real evapotranspiration) ranging from 14 mm d^{-1} (full irrigation conditions) to nearly 6 mm d^{-1} (deficit irrigation, Hanson et al., 2007) have been recorded in alfalfa crops, although drought tolerance varies considerably with genotype and phenological stage (Geerts and Raes, 2009). Alfalfa can withstand rather long periods of water deficit by halting its vegetative growth (Sheaffer et al., 1988) and accessing deep water resources with well-developed root systems (Volaire, 2008).

Irrigation is becoming a common practice in restoration works. Usually, support irrigation is implemented during summer droughts to ensure plant growth on recently restored slopes. In the case of stony substrates used for restoration in semi-arid areas, the response of vegetation to irrigation is a topic of particular interest, because conditions combine adverse topography, shallow and dry soils, and the need to increase plant cover under unfavourable hydrological situations.

The application of lysimeters in experiments concerning water and solute flow processes has been extensively reported (Cameron et al., 1992). Although they are important to assess water balance and effects of plant cover systems (Lanthaler, 2004), many studies rely on one or two lysimeter replicates and often draw conclusions from a single leachate event. But bulk soil hydraulic properties can vary considerably over short distances and within a closely defined soil (Simmonds and Nortcliff, 1998). The present study focused on leachate monitorization, which would allow a better evaluation of the environmental implications of the restoration practices. Since the results were obtained at lysimetric scale, they could only be applied to the usual irrigation practices in the area in an indirect way.

The present paper intends to demonstrate the failure of common opencast restoration practices in Mediterranean semi-arid areas. The experiment mimics usual scenarios in limestone quarries of NE Spain, i.e., the simultaneous occurrence of three conditions: (i) overburden and residual materials amended with organic matter used as substrates, (ii) sowing of fast-growing species used for erosion control and (iii) support irrigation during the first summer drought after sowing. The aim of this study was to compare vegetation development between two types of stony substrates, and with two different procedures concerning support irrigation.

2. Materials and methods

The experiment was performed with 30 lysimeters laid at random under open air conditions in a limestone quarry in Garraf (SW of Barcelona, NE Spain, about 10 km from the coastline, and 350 m asl). During one year (starting in autumn), the lysimeters were kept on a horizontal platform of compacted aggregates. A pipe installed under the lysimeters drained the leachates to a tank placed 0.75 m below. Each lysimeter consisted of a PVC pot with a 150 L capacity, cross section of 0.332 m^2 and 0.5 m of height. The bottom of each pot was filled with 0.10 m of gravel which was then covered with a 0.4 m layer of substrate.

Fifteen lysimeters were filled with substrate quarry waste and fifteen were filled with fine waste. All the lysimeters were sown with the same seed mixture and density and a part of them were irrigated according to the experimental design (cf. Sections 2.2 and 2.3).

2.1. Substrate characteristics

Two substrates were prepared with mine spoil, according to the usual practices: quarry waste (QW), a mixture of residual soils, limestone and other overburden materials without economic value, and fine waste (FW), a mixture of gravel by-products and residual small particles resulting from crushing and sorting processes. Both mine spoils had been homogeneously mixed with dried sewage sludge at a rate of 170–300 tn ha^{-1} (Hereter et al., 2005), respecting the European directive (ENV.E. 3/LM April 2000).

The physical and chemical characteristics of the substrates are shown in Table 1. Methodologies used for characterisation were as follows: gravel (wt/wt, sieving through a 2 mm sieve size); surface stoniness (point-count method over selected photographs from four replicates); particle size (pipette method, Guillet and Rouiller, 1982 according to the USDA system); organic carbon (Nelson, 1996); calcium carbonate (HCl treatment); total N (Kjeldahl method) and available P (Olsen method); electrical conductivity (from weight: volume 1:5 soil-water extract); water retained at θ_{1500} kPa and θ_{33} kPa (estimated from Saxton and Rawls, 2006, pedotransfer function). The last value was compared with water content in lysimeters two days after intense rainfalls.

2.2. Sowing and vegetation response

At the beginning of the experiment (20 September) three fast-growing perennial hemicryptophytes frequently used in restoration seeding mixtures were sown onto the 30 lysimeters: tall fescue (*Festuca arundinacea*), orchardgrass (*Dactylis glomerata*), and alfalfa (*Medicago sativa*). Seed application rate was 30 g m^{-2}, evenly distributed among the three species (5000, 13,000 and 4250 seeds m^{-2}, respectively). One day later, 20 lysimeters were irrigated with 20 mm of water.

A 0.04 m^2 metal grid (1 cm × 1 cm) was fixed over each lysimeter in order to evaluate the response of individual plants. The germination percentage was calculated considering the number of sown seeds of each species. Seedling emergence was measured two months after sowing.

Total plant cover was determined using the contact point method (Gounot, 1969). An observation was made every 5 cm along two perpendicular transects established on the surface of each lysimeter, with a total of 20 observations per lysimeter. Observations were made in March (adult plant) and August (end of the experiment).

To assess the growth of plant populations over time, the non-destructive parameter, density of total basal shoots per square metre (DTBS, Derner and Briske, 1999), was used. Total basal shoots was considered as the sum of photosynthetic tillers (in the case of *F. arundinacea* and *D. glomerata*) and photosynthetic basal shoots (in the case of *M. sativa*). Population growth was measured monthly

Table 1
Average and standard deviation of main physical and chemical characteristics of the two substrates used in the study. Number of replicates used for these determinations is $N = 5$ for all parameters.

Soil parameters	Units	Quarry waste (QW)		Fine waste (FW)	
		Average	Std	Average	Std
Gravels (> 2 mm)	$g\,kg^{-1}$	650.7	13.9	798.4	22.2
Rock fragment cover	%	97	7	49	7
Clay (<0.002 mm)	$g\,kg^{-1}$	231.5	12.9	177.8	3.6
Fine silt (0.02–0.002 mm)	$g\,kg^{-1}$	194.3	3.3	148.5	4.6
Coarse silt (0.05–0.02 mm)	$g\,kg^{-1}$	111.7	5.6	43.1	2.7
Total sand (2–0.05 mm)	$g\,kg^{-1}$	462.5	12.5	630.7	7.2
Textural class (USDA)		Loam		Sandy loam	
$CaCO_3$	$g\,kg^{-1}$	596.4	33.4	747	32
Organic C	$g\,kg^{-1}$	12.53	1.97	15.78	3.94
N (total)	$g\,kg^{-1}$	2	0.2	2.8	0.2
P (available)	$mg\,kg^{-1}$	139.8	24.7	240	11.1
Electrical conductivity 25 °C	$dS\,m^{-1}$	0.63	0.04	0.95	0.06
Water retained at θ_{33} kPa[a]	v/v	0.2621		0.2209	
Water retained at θ_{1500} kPa[a]	v/v	0.1395		0.1208	

[a] Estimated parameters from Saxton and Rawls (2006) (pedotransfer function).

from February to August. Observations made between June and August were used to evaluate the effect of irrigation.

Surface crust occurrence was checked at the same time as vegetation monitoring, and recorded whenever a metal instrument was needed to break the surface of the substrate. At the end of the experiment, the lysimeters were emptied (late August and early September) and qualitative information was then recorded on the status and distribution of the root system.

2.3. Statistical methods

Seedling emergence was analysed (two-way ANOVA) according to substrate type and irrigation regime (cf. Section 2.2). The Kolmogorov–Smirnov test was used to verify the normal population distribution. Data were arcsine of square root transformed when necessary to meet homogeneity of variance.

Population growths were subjected to a repeated measures analysis of variance. Sampling frequency was taken as the within-subject factor and substrate type as the between-subject factor. The Kolmogorov–Smirnov test was used to verify the normal population distribution. Data were square root of $(x+1)$ transformed when necessary to meet homogeneity of variance. Since DTBS values of July and August did not present a normal distribution, paired samples (non-irrigated versus irrigated) were compared using the nonparametric Mann–Whitney *U* test for each month.

2.4. Irrigation dosage, substrate moisture and leachate monitoring

For each substrate type, five lysimeters received no irrigation after sowing (non-irrigated). The other ten lysimeters received support irrigation (irrigated) after sowing (20 mm) and during summer, following the local and empirical watering practices. Three summer doses (20 mm each) were supplied: 22 June (28 days after the last precipitation), 12 July and 1 August. The total water volume applied as support irrigation was approximately 10–15% of ET0 (potential evapotranspiration) of that period. Tap water was used to irrigate (maximum electrical conductivity $\leq 6.2\,dS\,m^{-1}$ at 20 °C)

The monitoring campaigns of substrate water content were carried out on three occasions: (i) autumn (cool and wet period, from 20 September to 29 November); (ii) spring (wet and hot period, from 27 April to 25 May); and (iii) summer (dry and very hot period from 26 May to 25 August). Soil water content was measured weekly in the lysimeters using a permanent three-pronged TDR probe (Topp et al., 1980), at a depth of 20 cm. A parallel calibration was conducted at laboratory scale, given the high stoniness of the substrates (Drungil et al., 1989). The correlations obtained between TDR and volumetric moisture (oven dry) were $R^2 = 0.974$ for QW and $R^2 = 0.887$ for FW (Rubio et al., 2007).

Meteorological water budget (P-ET0) was estimated for the study period using data obtained from the nearby weather station at Begues (UTM 31 T 408696E, 4571567N and 563 m asl).

The seepage water was collected and measured during autumn. After each rainfall event (with a few exceptions, when two or more close precipitation events were accumulated) seepage water was measured directly. Results are presented as the cumulative water column ($L\,m^{-2} = mm$).

3. Results

Values of precipitation and potential evapotranspiration recorded during the study period are presented in Table 2 and substrate water content in Fig. 1a and b. Autumn and winter were wet (average water budget +1.75 $mm\,d^{-1}$ and +0.60 respectively), spring was dry ($-2.45\,mm\,d^{-1}$) and summer (period starting on the day after the first dosis of support irrigation) was very dry ($-3.90\,mm\,d^{-1}$).

Average water content in QW-non-irrigated lysimeters (22.6 mm) was slightly higher than in FW-non-irrigated ones (18.5 mm), and they were well correlated ($R^2 = 0.842$).

Table 3 shows the average volume of collected leachate. Nearly 40% of precipitation was collected and a simple linear regression between precipitation and leachate was found, with a high coefficient of determination ($R^2 = 0.96$).

Soil crust occurrences were observed on several occasions during the study, especially after rain events. Crusts occurrences in FW were more frequent than in QW during the germination period.

3.1. Germination

Total germination percentage presented a significant interaction between substrate and irrigation ($p = 0.028$). When support irrigation was applied, the germination on FW substrate doubled but it increased only by 10% on QW. Overall germination was significantly higher in QW substrate than in FW ($p = 0.000$). Irrigation also determined more germination than non-irrigation ($p = 0.001$) (see Fig. 2). When the analysis was carried out separately for each species a significant interaction between substrate type and irrigation was also found: *F. arundinacea* ($p < 0.001$) and *M. sativa*

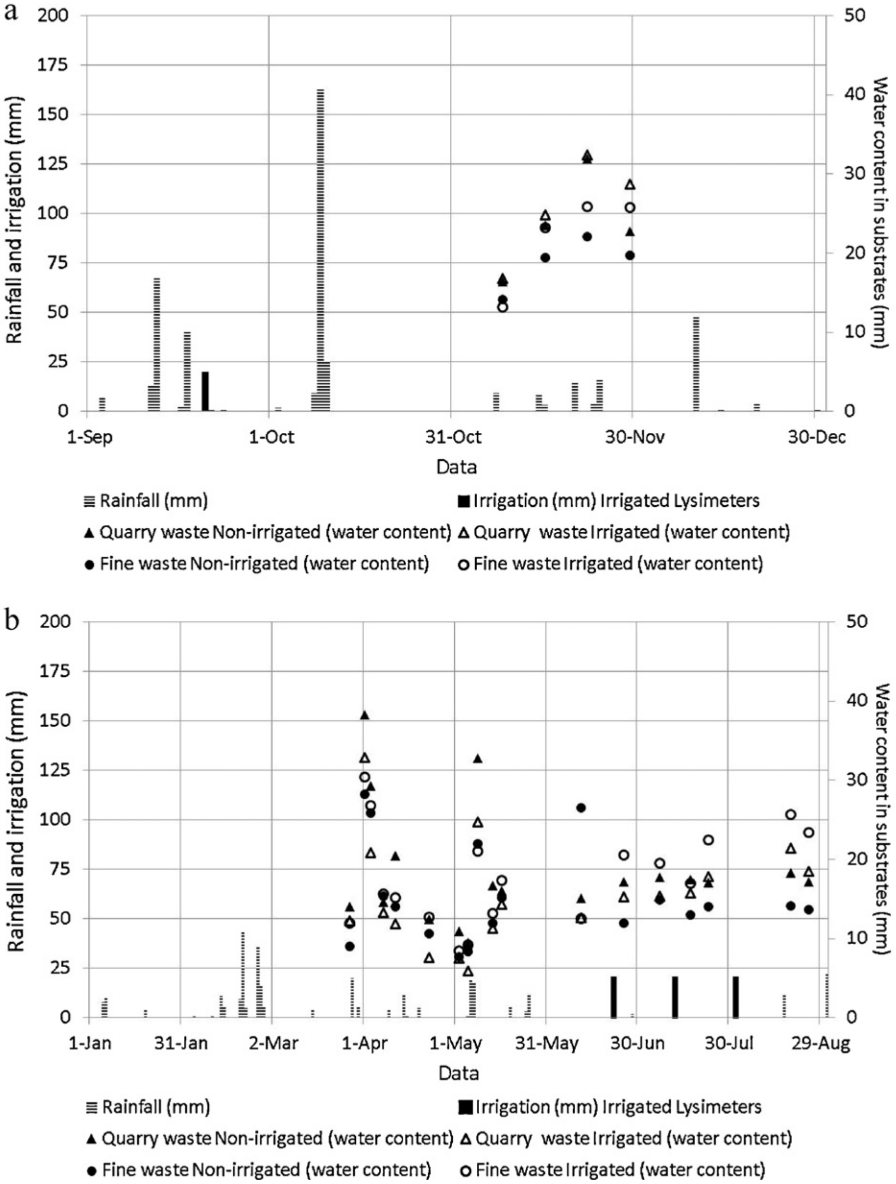

Fig. 1. (a) Irrigation, rainfall and water content in substrates (0–0.20 m) during the initial period (autumn). (b) Irrigation, rainfall and water content in substrates (0–0.20 m) during springtime and summer.

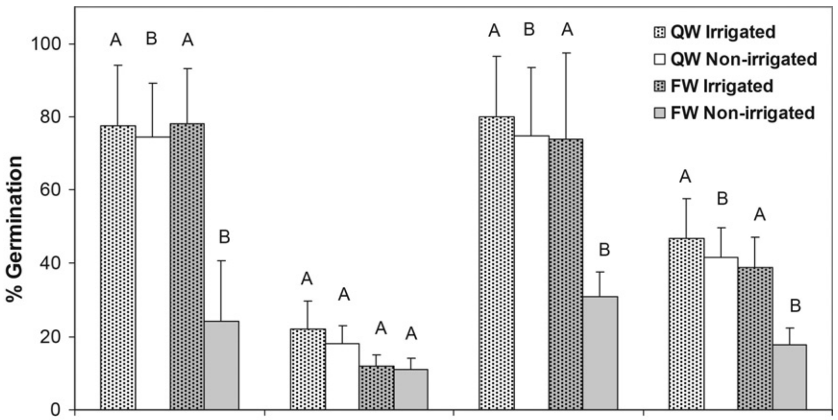

Fig. 2. Percentage of germination two months after seeding (average and standard deviation) of each species and total values.

Table 2
Amounts of rainfall, irrigation and potential evapotranspiration recorded during the monitored periods at the experimental site.

	Duration days	Cumulative rain mm	Irrigation mm	Raining days days	Average precipitation mm d^{-1}	Maximum rainfall mm d^{-1}	Accumulated ET0 mm	Average ET0 mm d^{-1}
Autumn	91	317.9	20[a]	15	21.2	163.6	158.4	1.7
Winter	89	168.3	0	15	11.2	43.9	114.4	1.3
Spring	91	113.1	0	12	9.4	20.1	335.8	3.7
Summer	78	65.6	60	7	9.4	22.5	381.4	4.9

[a] Initial irrigation, after sowing ("irrigation" treatment).

Table 3
Values of precipitation (in mm), volume of leachate (in mm) collected during the initial period of the experiment (autumn) and water content (mm) in the two types of substrates after rains. Values for precipitation and leachate (mm) are cumulative between consecutive dates of collection.

Date	Precipitation	Quarry waste (QW)		Water in substrate	Fine waste (FW)		Water in substrate
		Leachate Average	Std		Leachate Average	Std	
20-September	43.4	19	12		10	6	
27-September	2.4	5	5		4	3	
06-October	2.0	2	2		1	1	
11-October	199.1	62	20		72	24	
08-November	9.7	2	2		1	2	
19-November	13.4	2	2		7	4	
22-November	0			32.23			24.05
23-November	15.4	16	7		11	6	
26-November	20.5	14	13		7	9	
29-November	0			25.78			22.79

($p = 0.014$). For all species, QW substrates presented higher germination values than FW (two-way ANOVA; substrate: $p < 0.05$). However, *F. arundinacea* and *M. sativa* presented lower germinations in non-irrigated lysimeters than in irrigated ones (two-way ANOVA; irrigation: $p < 0.05$). According to the germination percentage, the three species were ranked as follows: *F. arundinacea* = *M. sativa* > *D. glomerata* (see Fig. 2).

3.2. *Plant growth and cover*

The evolution of DTBS, ET0 and substrate humidity was monitored monthly during spring and summer (see Fig. 3).

These relationships were independent of the type of substrate. DTBS and substrate humidity decreased simultaneously ($R^2 = 0.55$). We also found a negative correlation between ET0 and DTBS (QW: $R^2 = 0.95$; FW: $R^2 = 0.94$).

The maximum development of vegetation was reached in February–March (see Fig. 3), after a mild winter enabling plant density increased in springtime. While ET0 values were $\leq 4\,\text{mm}\,\text{d}^{-1}$, the vegetation developed a very dense cover. From April onward, the spring became dry and water stored in the substrate decreased (Fig. 1b), leading to a 40% reduction of the DTBS in May and June.

In June and July, the water content in the rooting zone (20 cm) (see Fig. 1b) reached values similar to March, but plant density (DTBS) fell to 1000. In August, the evaporative demand increased to more than $4\,\text{mm}\,\text{d}^{-1}$ and DTBS kept decreasing to values close to zero.

In short, from March to June DTBS decreased continuously and significantly (84%, see Fig. 3), but this trend did not depend on the type of substrate (ANOVAr, $F_{1,28} = 0.015$; $p > 0.05$). There were clearly two steps in such reduction: from April to May and from May to June.

Globally, irrigated lysimeters presented significantly higher DTBS (about 100) than non-irrigated ones (though only slightly significant, $p = 0.051$) in July and August (Fig. 3), but support irrigation was not sufficient to maintain water transfer from the substrate to plants and to prevent their death.

At species level, *F. arundinacea* was the dominant species until June (Fig. 4a and b), dropped dramatically to 23% in July and disappeared just after August irrigation. Substrate type or summer support irrigation did not determine different densities of tillers. *Dactylis glomerata* population in July was reduced to 53%, relative to June, kept declining at the beginning of August and had almost disappeared by the end of this month. In this case, the density of tillers was always higher in QW (ANOVAr, $F_{1,28} = 35.75$; $p = 0.00$), but irrigation had no effect (July: $U = 80$, $p > 0{,}05$; August: $U = 90$, $p > 0{,}05$). *Medicago. sativa* declined in a similar way but some individuals survived until the end of August (43 DTBS). The density of *M. sativa* basal shoots was always higher in FW (ANOVAr, $F_{1,28} = 28.02$; $p = 0.00$) than in QW, but summer irrigation had no effect (July: $U = 70$, $p > 0{,}05$; August: $U = 70$, $p > 0{,}05$).

The type of substrate did not determine significantly different cover levels over time. In March, plant cover was continuous (96%), but it underwent a dramatic decline until August (Table 4), when values were below 10%. Support irrigation led to a higher cover in both substrates ($p = 0.014$).

At the end of the experiment, there was no evidence of regrowth for *F. arundinacea* despite the favourable weather conditions which had occurred since the last plant monitoring (60 mm precipitation, average daily ETr 3.8 mm). In contrast, *M. sativa* roots were reaching the bottom of the lysimeters (approximately 40 cm deep).

Table 4
Plant cover (%) during the experiment, according to the two tested substrates and two irrigation treatments.

		March	August
QW	Non-irrigated	98.89 ± 2.49 a	0.00 ± 0.00 a
	Irrigated	96.66 ± 2.87 a	3.89 ± 6.44 b
FW	Non-irrigated	94.44 ± 0.00 a	1.11 ± 2.49 a
	Irrigated	97.22 ± 2.93 a	10.56 ± 8.86 b

Different lowercase letters indicate a significant difference between irrigation treatments ($p < 0.05$, Mann–Whitney *U* test).

QW: quarry waste, a mixture of residual soils, limestone and other overburden materials without economic value. FW: fine waste a mixture of gravel by-products and residual small particles resulting from crushing and sorting processes.

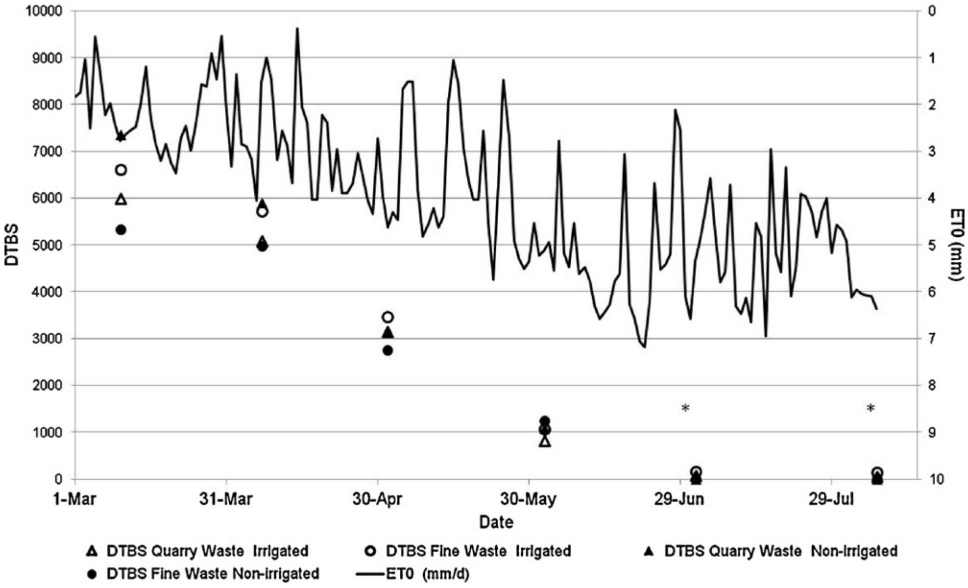

Fig. 3. Density of total basal shoots (DTBS) and evapotranspiration values (mm d^{-1}). Significant differences (*) were only found between irrigated and non-irrigated lysimeters in July and August.

4. Discussion

The tested substrates showed some physical limitations which had a negative influence on vegetation growth. Differences in germination percentages between substrates should be interpreted considering the effects of soil crust formation (Awadhwal and Thierstein, 1985). At various stages of the experiment we observed crusts, especially in FW substrate. Initial water application by irrigation reduced the crust impedance and at same time facilitated plant emergence. Higher germination values were reached in QW than in FW. In March however, FW vegetation presented a development similar to the rest of treatments, a possible consequence of the autumn-winter rains which might have compensated for the initial lower development.

However, QW substrate seemed to have some more favourable characteristics (less gravel and higher clay proportion). These results indicate that differences in clay and silt contents do not determine substrate response to rain events, water availability or development state of the vegetation by the end summer.

Adding to these physical limitations, the installed vegetation system was not able to maintain a dense cover through a long dry period. Under real conditions (embankments with high slopes), the protection provided by the herbaceous layer (splash erosion control and mechanical anchoring of roots) may be insufficient to face the intense autumn rainfalls. The introduced herbaceous plants were perennial, fast-growing species with high productivity, and they achieved satisfactory germination percentages and speeds, but they disappeared almost completely by the end of the cycle, even with support irrigation.

Among the three species, *D. glomerata* exhibited the poorest response although it had the highest number of seeds, more than double. On the other hand, germination percentages of *M. sativa* and *F. arundinacea* were similar and above 70%. *Medicago sativa* population decreased drastically in March, but persisted until the end of summer, while *F. arundinacea* disappeared in August even though it had been dominant since November. After Torbert, 1990 and Volaire and Lelièvre (2001), root system length at the beginning of summer affects plant survival directly. Field observations at the end of the experiment agree with this finding. A few roots of *D. glomerata* were located within the top 20 cm of substrate, whereas many roots of *M. sativa*, which was the most abundant species at the end of the cycle, grew to almost 40 cm m in depth.

Another aspect to be taken into consideration is the suitability of these three species for Mediterranean climate conditions. Some monospecific swards of *D. glomerata* or *F. arundinacea* can survive periods of drought due to some eco-physiological strategies (Volaire and Norton, 2006). Both *M. sativa* and *F. arundinacea* are generally regarded as drought tolerant species (Volaire, 2008; Hanson et al., 2007), yet in our study the latter completely disappeared when water availability decreased. This has also been observed by other authors for similar drought conditions, especially in experiments that restricted root system growth (Volaire and Lelièvre, 2001).

Weltz et al. (1998) consider that a certain threshold of plant cover ensures the effective surface protection of restored banks. Vegetation cover below this threshold corresponds to conditions of potential risk of erosion driven by the typically intense Mediterranean autumn rains.

The support irrigation doses (nearly 15% of the summer ET0) and frequencies (20 days) used in the experiment were similar to the usual practices in the area, and did not contribute to improve plant cover. This lack of response to support irrigation can be attributed to several reasons.

First, there was a pronounced water deficit during the studied spring and summer periods. This is an irregular pattern but not uncommon in Mediterranean climates. Spring rains are usually present but sometimes they fail, as in this case. Thus in spring, the water present in the substrate practically corresponded to the one accumulated during the previous autumn. Accumulated water deficit in summer was 255.8 mm. Although ET0 demand used to calculate this water balance was the potential evapotranspiration and the real ET could be lower, the water deficit is unlikely to differ substantially from that given here. However, the evolution of the vegetation was closely related with daily ET0: DTBS was reduced by 30% when daily ET0 was 3.8 mm d^{-1} and the vegetation disappeared when ET0 was >5 mm d^{-1}.

Other reasons lie in some characteristics of the substrates. Estimated available water storage capacity was approximately 1 mm cm^{-1} (estimated during the leachate determinations, see

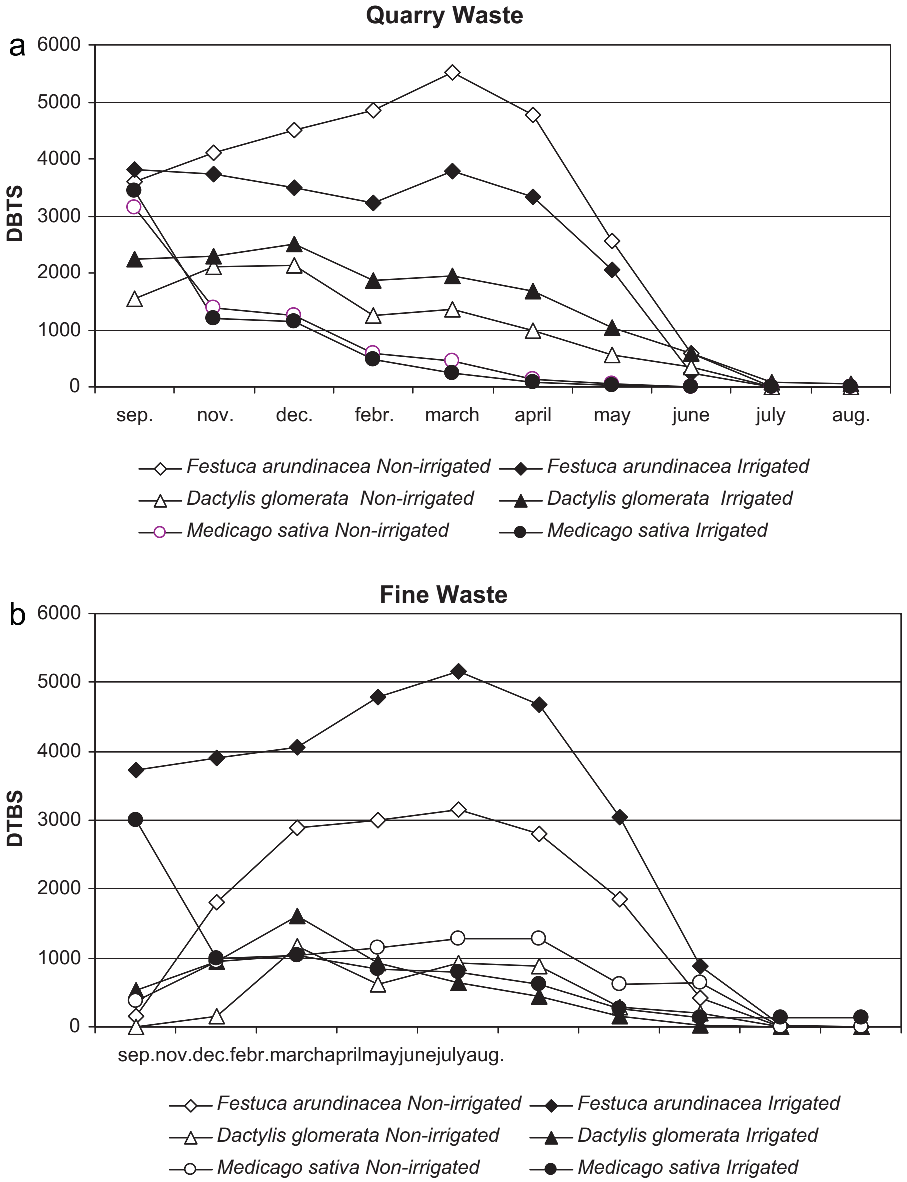

Fig. 4. (a) Evolution of the density of total basal shoots (DTBS) over time for the three sown species (average values), quarry waste substrate (QW) and two irrigation treatments (irrigated; non-irrigated). (b) Evolution of the density of total basal shoots (DTBS) over time for the three sown species (average values), fine waste substrate (FW) and two irrigation treatments (irrigated; non-irrigated).

Table 3). This value is low and, consequently, the volume of leachate was high (autumn period).

Lastly, the irrigation system used was wasteful. The volumes of water applied were relatively high (20 mm per application). Irrigation conditions led to water loss by infiltration (very high hydraulic conductivity). Stoniness inside soil reduces the total pore volume of the soil and water availability may be limited (Van Wesemael et al., 2000).

Doses and frequencies of watering in this experiment are usual in quarries, especially in those not equipped with sprinkling irrigation systems. Under such conditions, high doses and low frequency are means to reduce the costs of water transport and application. This implies some risks, in this case watering was applied some days after permanent wilting point of substrate that was attained in all treatments (irrigated and non-irrigated). Lysimeters irrigated in July and August did not succeed in maintaining higher DTBS than non-irrigated ones (density of about 100 DTBS).

Considering that the daily ET0 was greater than 5 mm d^{-1} when vegetation disappeared, and that the vegetation remained at 1000 DTBS when ET0 was 3.85 mm d^{-1}, watering should have provided approximately about 1 or 2 mm per day from June on, to maintain the same green cover observed in May.

Under such circumstances, a potentially sufficient number of plants would complete their growth cycle during summer and develop canopies and root systems capable of controlling the erosion caused by autumn rainfalls.

This implies providing minimum weekly amounts of water ranging from 7 to 14 mm. As it happened, the total water supplies were insufficient to maintain this type of vegetation throughout the summer period. On the other hand, water losses by leaching should have been prevented, considering substrate characteristics.

Another aspect to consider is the effect of this type of hydrological dynamics on the next stages of the restoration. The establishment of herbaceous vegetation represents the first stage of the restoration of a mining area but the typical woody species of Mediterranean ecosystems should be introduced as soon as possible (Maestre and Cortina, 2004; Badía et al., 2007).

The results suggest that the rapid development of a dense herbaceous cover of fast-growing species may rapidly exhaust the scarce water reserve of substrates and thus restrict the development of other species with greater interest for the local plant succession (Oliveira et al., 2011). For example, in our short-term experiment, the considerable growth of *F. arundinacea* limited the development of *D. glomerata* and *M. sativa* over time. The two latter species grew only when *F. arundinacea* disappeared.

There is therefore a contradiction between the theoretical goals (at short and long term: erosion control and increased diversity) and the actual praxis of the real restoration (blocky and stony substrates, limited effective water supply and fast plant growth). Considering the presented results, some possible alternatives may be established to increase success in the revegetation of embankments in the Mediterranean area.

One option would be to use substrates with a particle size distribution (increasing the fine fraction) that allows long term water storage. Results show that a 15% difference in stoniness does not affect the evolution of the herbaceous cover (Fig. 4a and b) and that substrates with more than 50% of fine materials should probably be selected to effectively increase water retention and reduce percolation. However, spoils do not usually include such substrates (at least in the required quantities) and they must be purchased externally. There may be other options to improve the water capacity of these stony substrates such as the use of hydrogels (Rowe et al., 2005) or the application of organic mulch over stony soils.

Another solution is to meet the requirements of the herbaceous species in the summer through adequate irrigation frequencies and doses. The objective would be to maintain an efficient plant covers before autumn rainfalls, potentially aggressive. But this can also represent a significant increase in the total costs of the restoration action and, in our case at least, such an irrigation scheme would more than double them. However, this approach may not be suitable for this region (and semiarid alike regions), where it is imperative to manage water resources properly during the dry periods.

Possibly less expensive and more environmentally sustainable procedure would be the introduction of species better adapted to the target substrates and to the local Mediterranean conditions, an option already proposed by different authors (Tormo et al., 2007; Moreno et al., 2008). However, this option is not always commercially supported, because the availability of alternative plant materials is reduced and field experiments under these conditions are still scarce. So far, the current practice relies on fast growing species, even if it is inefficient (Balaguer, 2002; Garcia-Palacios et al., 2010; Mola et al., 2011).

5. Conclusions

In the reclamation process of limestone quarries in dry Mediterranean areas, a balance must exist among elements of the new ecosystem: plant cover development and substrate capacity to support it in critical periods. An effective equilibrium must be established between short and long term goals (control of erosion and similarity with the reference plant community) and the actual capacity of the substrate to supply water to a plant community.

Interactions between substrate, climate and vegetation based on the restoration objectives should be considered in the design of revegetation plans. This is particularly important in the Mediterranean area where water availability is restricted and where the erosion risk is very high in autumn.

For substrates with very low water-storage capacity, such as those used in limestone quarries, it is not advisable to aim at a continuous and dense herbaceous cover composed of species that are not drought tolerant.

A dense plant cover protects the embankments against erosion, but it also consumes large amounts of water in summer. If sufficient support irrigation doses are not applied for economical or ecological reasons, summer drought destroys the plant cover and drastically reduces its capacity to protect slopes against the erosion in autumn.

Although a continuous and dense ground cover may help to control erosion on the short term, it is obtained at the expense of significant water supplies. Moreover, it may hinder spontaneous establishment, e.g. from autochthonous species. Planning of revegetation works in Mediterranean limestone quarries should contemplate the use of species that are better adapted to drought (climatic and edaphic), thus having less demanding water requirements, and hopefully not compromising natural colonisation.

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References

Albaladejo, J., Alvarez, J., Querejeta, J., Díaz, E., Castillo, V., 2000. Three hydro seeding revegetation techniques for soil erosion control on anthropic steep slopes. Land Degrad. Dev. 11, 315–325.

Annicchiarico, P., Pecettia, L., Abdelguerfi, A., Bouizgaren, A., Carronid, A.M., Hayeke, T., M'Hammadi Bouzinaf, M., Meznig, M., 2011. Adaptation of landrace and variety germplasm and selection strategies for Lucerne in the Mediterranean basin. Field Crop Res. 120, 283–291.

Awadhwal, N.K., Thierstein, G.E., 1985. Soil crust and its impact on crop establishment: a review. Soil Till. Res. 5, 289–302.

Assuero, S.G., Matthew, C., Kemp, P., Barker, D.J., Mazzanti, A., 2002. Effects of water deficit on Mediterranean and temperate cultivars of tall fescue. Aust. J. Agric. Res. 53, 29–40.

Badía, D., Valero, R., Gracia, A., Martí, C., Molina, F., 2007. Ten-year growth of woody species planted in reclaimed mined banks with different slopes. Arid Land Research and Management 21 (1), 67–79.

Balaguer, L., 2002. Las limitaciones de la restauración de la cubierta vegetal. Ecosistemas 11, Available from http://www.revistaecosistemas.net (accessed 13.09.2008).

Barker, D.J., Caradus, J.R., 2001. Adaptation of forage species to drought. In: Proceedings of the XIX International Grassland Congress—Grassland Ecosystems: An Outlook into the 21st Century, pp. 241–246.

Bartholomew, P.W., Williams, R.D., 2006. Effects of exposure to below-freezing temperatures, soil moisture content and nitrogen application on phyllochron in cool-season grasses. Grass Forage Sci. 61, 146–153.

Bertiller, M.B., Zaixso, P., Irisarri, M.P., Brevedan, E.R., 1996. The establishment of *Festuca pallescens* in arid grasslands in Patagonia (Argentina): the effect of soil water stress. J. Arid Environ. 32, 161–171.

Bradshaw, A.D., Chadwick, M.J., 1980. The Restoration of Land: The Ecology and Reclamation of Derelict and Degraded Land. Blackwell Scientific Publications, Oxford.

Cameron, K.C., Smith, N.P., McLay, C.D.A., Fraser, P.H., McPherson, R.J., Harrison, D.F., Harbottle, P., 1992. Lysimeter without edgeflow: an improved design and sampling procedure. Soil Sci. Soc. Am. J. 56, 1625–1628.

Clemente, A.S., Werner, C., Máguas, C., Cabral, M.S., Martins-Loução, M.A., Correia, O., 2004. Restoration of a limestone quarry: effect of soil amendments on the establishment of native Mediterranean sclerophyllous shrubs. Restor. Ecol. 12, 20–28.

Derner, J.D., Briske, D.D., 1999. Interclonal regulation in aperennial caespitose grass, a field evaluation of above- and below-ground resource availability. J. Ecol. 87, 675–696.

Drungil, C.E.C., Abt, K., Gish, T.J., 1989. Soil moisture determination in gravelly soils with time domain reflectometry. Trans. ASAE 32, 177–180.

Duckworth, G.D., Altwegg, R., Guo, D., 2010. Soil moisture limits foraging: a possible mechanism for the range dynamics of the hadeda ibis in southern Africa. Diver. Distrib. 16, 765–772.

Ervin, E.H., 1998. Drought avoidance aspects and crop coefficients of Kentucky bluegrass and tall fescue turfs in the semiarid west. Crop Sci. 38, 788–795.

European Directive and document, ENV.E. 3/LM April 2000.

Garcia-Palacios, P., Soliveresa, S., Maestrea, F.T., Escuderoa, A., Castillo-Monroya, A.P., Valladares, F., 2010. Dominant plant species modulate responses to hydroseeding, irrigation and fertilization during the restoration of semiarid motorway slopes. Ecol. Eng. 36, 1290–1298.

Geerts, S., Raes, D., 2009. Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agric. Water Manage. 96, 1275–1284.

Gonzalez-Dugo, V., Durand, J.L., Gastal, F., 2005. Short-term response of the nitrogen nutrition status of tall fescue and Italian ryegrass swards under water deficit. Aust. J. Agric. Res. 56, 1269–1276.

Gounot, M., 1969. Méthodes d'étude quantitative de la végétation. Mason, Paris.

Guillet B, Rouiller J., 1982. Particle size analysis. In: Bonneau, M., Soucier, B. (Eds.), Constituents and Properties of Soil. Academic Press, London, pp. 261–267.

Hanson, B., Putnam, D., Snyder, R., 2007. Deficit irrigation of alfalfa as a strategy for providing water for water-short areas. Agric. Water Manage. 93, 73–80.

Hereter, A., Josa, R., Jorba, M., Vallejo, R., 2005. Caracterización química de sustratos de restauración de actividades mineras con aplicación de enmiendas orgánicas sólidas y líquidas. In: Jiménez-Ballesta, R., Álvarez González, M.A. (Eds.), Control de la degradación del suelo. Universidad Autónoma de Madrid. Julio, ISBN: 84-689-2620-5, pp. 401–405.

Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setala, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecol. Monogr. 75, 3–35.

Jorba, M., Vallejo, R., 2008. The ecological restoration of quarries: a case with application of organic amendment and irrigation. Ecosistemas 17, 119–132.

Khater, C., Martin, A., Maillet, J., 2009. Spontaneous vegetation dynamics and restoration prospects for limestone quarries in Lebanon. Appl. Veg. Sci. 6, 199–204.

Lanthaler, C., 2004. Lysimeter Stations and Soil Hydrology Measuring Sites in Europe: Purpose, Equipment, Research Results Future Development. Thesis for the degree of Magistra der Naturwissenschaften, Graz.

Maestre, F.T., Cortina, J., 2004. Do positive interactions increase with abiotic stress? A test from a semi-arid steppe. Proceedings of the Royal Society of London. B271(Suppl.), S331–S333.

McCarty, L.B., 1991. Daily tall fescue leaf appearance rate in relation to environmental factors. HortScience 26, 114–117.

Ministerio de la Presidencia, 2009. RDL 975/2009 de 12 de Junio, sobre gestión de residuos de las industrias extractoras y de protección y rehabilitación del espacio afectado por actividades mineras. BOE Núm. 143. Sección I, pp. 49948–49993.

Mola, I., Jiménez, M.D., López-Jiménez, N., Casado, M., Miguel, A., Balaguer, L., 2011. Roadside reclamation outside the revegetation season: management options under schedule pressure. Restor. Ecol. 19, 83–92.

Moreno de las Heras, M., Nicolau, J.M., Espigares, T., 2008. Vegetation succession in reclaimed coal-mining slopes in a Mediterranean-dry environment. Ecol. Eng. 34, 168–178.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon and organic matter. In: Sparks, D.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. American Society of Agronomy and Soil Science Society of America, Madison, pp. 1011–1069.

Oliveira, G., Nunes, A., Clemente, A., Correia, O., 2011. Testing germination of species for hydroseeding degraded Mediterranean areas. Ecol. Restor., doi:10.1111/j.1526-100X.2011.00816.x.

Rowe, E.C., Williamson, J.C., Jones, D.L., Holliman, P., Healey, J.R., 2005. Initial tree establishment on blocky quarry waste ameliorated with hydrogel or slate processing fines. J. Environ. Qual. 34, 99.

Rubio, C., González-Flor, C., Josa, R., 2007. Monitorización del contenido de agua en los sustratos de restauración minera:calibración de las medidas de TDR en laboratorio y campo. In: Giráldez Cervera, J.V., Jiménez Hornero, J. (Eds.), Estudios de la Zona No Saturada del Suelo, vol. VIII, pp. 161–166.

Saxton, K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70, 1569–1578.

Sheaffer, C.C., Tanner, C.B., Kirkham, M.B., 1988. Alfalfa water relations and irrigation. In: Hanson, A.A., Barnes, D.K., Hill, R.R. (Eds.), Alfalfa and Alfalfa Improvement. ASA-CSSA-SSSA Publishers, Madison, WI, pp. 373–409.

Simmonds, L.P., Nortcliff, S., 1998. Small scale variability in the flow of water and solutes, and implications for lysimeter studies of solute leaching. Nutr. Cycl. Agroecosys. 50 (65–75), 65.

Topp, G.C., Davis, J.L., Annan, A.P., 1980. Electromagnetic determination of soil water content: measurements in coaxial transmission lines. Water Resour. Res. 3, 574–582.

Torbert, H.A., 1990. Fescues with large roots are drought tolerant. Appl. Agric. Res. 5, 181–187.

Tormo, J., Bochet, E., Garcia-Fayos, P., 2007. Roadslope revegetation in semiarid Mediterranean environments. Part II: topsoiling, species selection and hydroseeding. Restor. Ecol. 15, 97–102.

Van Wesemael, B., Mulligan, M., Poesen, J., 2000. Spatial patterns of soil water balance on intensively cultivated hillslopes in a semi-arid environment: the impact of rock fragments and soil thickness. Hydrol. Process. 14, 1811–1828.

Volaire, F., 2008. Plant traits and functional types to characterise drought survival of pluri-specific perennial herbaceous swards in Mediterranean areas. Eur. J. Agron. 29, 116–124.

Volaire, F., Lelièvre, F., 2001. Drought survival in *Dactylis glomerata* and *Festuca arundinacea* under similar rooting conditions in tubes. Plant Soil 229, 225–234.

Volaire, F., Norton, M., 2006. Summer dormancy in perennial temperate grasses. Ann. Botany 98, 927–933.

Weltz, M.A., Kidwell, M.R., Fox, H.D., 1998. Influence of abiotic and biotic factors in measuring and modeling soil erosion on rangelands: state of knowledge. J. Range Manage. 51, 482–495.

White, R.H., 1992. Competitive turgor maintenance in tall fescue. Crop Sci. 32, 251–256.