Full title: RESTORATION OF GYPSICOLOUS VEGETATION ON QUARRY SLOPES: GUIDANCE FOR HYDROSEEDING UNDER CONTRASTING INCLINATION AND ASPECT

Short title: RESTORATION OF GYPSICOLOUS VEGETATION ON QUARRY SLOPES

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Abstract

The establishment of gypsicolous vegetation of high conservation value on land impacted by quarrying requires restoration measures to overcome constraints imposed by the new landforms created in the process. The aim of this study was to assess the suitability of three standard hydroseeding methods to restore gypsicolous vegetation on quarry spoil slopes under a dry Mediterranean climate. The treatments were: paper cellulose mulch; paper cellulose mulch + organic blanket; and wood fibre mulch; compared against a control. These treatments were tested on two slopes (10-15% vs 60-65%) and two contrasting aspects (north vs south). We evaluated the cover of all plant species 2.8 years after treatment, assessing both target gypsicolous species and non-target species. Our results showed strong compositional and cover differences between hydroseeded and control plots. Control plots had a low cover of target species with a vegetation composed of early-successional species that had the potential to hinder target species establishment over time. All hydroseeding treatments improved target vegetation cover, with wood fibre performing best in most situations studied here, alternatives being the cheaper but less effective paper mulch on shallow slopes; or the more expensive paper mulch + blanket on steep slopes in case of high erosion risk. Shallow and southern-steep slopes were more suitable for the recovery of gypsum vegetation by hydroseeding, compared to northern-steep slopes where non-target species developed more readily outcompeting target species. These results will help to guide management decisions to restore gypsicolous vegetation by hydroseeding in disturbed gypsum habitats.

Keywords: Aspect, hydroseeding, gypsum habitat, restoration techniques, slope.

1. Introduction

The restoration of native vegetation affected by quarrying poses challenges due to limitations caused by the alteration of both topography and soil properties (Bradshaw, 2000). Quarrying usually produces low-quality spoil materials with inherent stability problems, both causing severe difficulties for the re-establishment of former vegetation (Martín-Duque et al., 2010; Espigares et al., 2011; Cohen-Fernández et al., 2013). Common practices to enhance vegetation establishment and stabilising slopes include the spreading of topsoil, use of geotextiles, and the planting or sowing of plants (Theisen, 1992; Singh et al., 2002; Ghose, 2004; Matesanz et al., 2006; Gilardelli et al.

2013). Hydroseeding is a common sowing technique for quarry and road-side rehabilitation that is increasingly used in ecological restoration; this approach often requires the use of various mulches, stabilisers, fertilizers as well as mixtures of commercial and native species seeds (Matesanz et al., 2006; Brofas et al., 2007; García-Palacios et al., 2010). The inclusion of native species is increasingly being used in restoration projects especially under adverse climatic and soil conditions (Matesanz & Valladares, 2007; Bochet et al., 2010; Oliveira et al., 2012), and is particularly relevant when the recovery of specific vegetation targets associated with singular substrates is the restoration goal (O'Dell & Claassen, 2009; Whiting et al., 2010; Ballesteros et al., 2014).

Gypsum substrates in arid and semi-arid regions are often important habitats for plant conservation that must be preserved (European Commission, 1992). These habitats support a highly-specialized flora with many rare and endemic species which have a range of strategies to cope with the physical and chemical limitations imposed by gypsum substrates (see Mota et al., 2011; Escudero et al., 2014). However, gypsum is a mineral in global demand (Herrero et al., 2013), and its extraction by mining inevitably damages the valuable gypsicolous vegetation and the habitat (Mota et al., 2011). Thus, mining companies are compelled to conduct restoration programs despite the lack of information on the most appropriate ecological restoration techniques and procedures. The restoration of gypsicolous flora affected by quarrying has been the focus of previous studies (Mota et al., 2004; Dana & Mota, 2006; Ballesteros et al., 2012, 2014). Spontaneous succession may take considerable time due to site-specific environmental conditions, as unstable and unsuitable substrates, lack of propagules or competition with non-target species (Mota et al., 2004; Dana & Mota, 2006; Prach & Řehounková, 2006; Gilardelli et al., 2015). Active measures such as planting (Ballesteros et al., 2014) and sowing (Ballesteros et al., 2012) have been shown to provide good restoration of gypsicolous plant communities, but they have mainly been implemented on relatively flat landforms. Techniques for successful restoration of steeper landforms have only been partially addressed (e.g. Pastor & Hernández, 2002; Martín et al., 2003; Matesanz & Valladares, 2007). However, gypsum quarry waste areas are often remodelled and usually have relatively steep slopes, which depending on orientation may differ greatly on surface temperature and water availability in Mediterranean climates (Kutiel, 1992; Pueyo & Alados, 2007; Alday et al., 2010). One way to tackle steep slopes is through hydroseeding; although hydroseeding is widely used in restoration, to our knowledge, there is limited technical or scientific literature resulting in specific guidelines that can be used to design restoration programs for disturbed gypsum habitats.

The aim of our study is to assess the suitability of three hydroseeding methods to restore gypsicolous vegetation affected by quarrying on spoil slopes under a dry Mediterranean climate. Our underlying hypothesis was that early vegetation response would be determined by interactions between the hydroseeding method, slope and site aspect. We hoped the results would inform future ecological restoration of spoil materials left after gypsum quarrying, allowing better designed and cost-effective future restoration programs.

2. Materials and Methods

2.1. Site description

The study was performed in an experimental area next to an active quarry in Escúzar, Granada, SE Spain (37° 2' 57'' N, 3° 45' 30'' W) at 950 m asl. The climate is continental Mediterranean, with relatively cold winters, hot summers, and four months of water deficit. The mean annual temperature is 15.1 °C, with an average monthly minimum temperature in January of 7.6 °C and maximum of 24.2 °C in August. Annual rainfall averages 420 mm, occurring mainly in winter. The area is in the Neogene sedimentary basin of Granada; the dominant substrates being lime and gypsum deposited in the late Miocene, the latter in combination with marls (Aldaya et al., 1980). The predominant soils in the gypsum outcrops are Gypsiric Leptosols (Aguilar et al., 1992; IUSS Working Group WRB, 2015). The vegetation of the area is a mosaic of fields with cereal crops and olive and almond orchards (*Olea europaea* L. and *Prunus dulcis* D.A. Webb.) and scattered patches of native plants growing over gypsum outcrops (Ballesteros et al. 212).

2.2. Target species

The target gypsicolous vegetation in the area is described in the EU Habitats Directive (European Commission, 1992) as 1520, “Iberian gypsum vegetation, *Gypsophiletalia*”, and is characterized by plants exclusive to gypsum soils (gypsophiles); (see Mota et al. 2011, Escudero et al. 2014), such as *Helianthemum squamatum* (L.) Dum. Cours., *Lepidium subulatum* L., and *Ononis tridentata* subsp. *crassifolia* (Dufour ex Boiss.) Nyman. In addition, there are also other frequent non-exclusive species of gypsum substrates (gypsovags) such as *Stipa tenacissima* L., *Rosmarinus officinalis* L., *Helianthemum syriacum* (Jacq.) Dum. Cours., *Thymus zygis* L. subsp. *gracilis* (Boiss.) R. Morales and *Teucrium capitatum* subsp. g*racillimum* (Rouy) Valdés Berm. & Sánchez Crespo (according to Marchal et al. 2008). Total plant cover in the habitat is approximately 42%, 30% for target species and 22% for gypsophiles (transforming Braun-Blanquet scale data in Marchal et al., 2008, following Van der Maarel 1979).

2.3. Experimental design

Experimental slopes were built in October 2011 on an area of 0.7 ha using spoil (see properties in Table S1), derived from gypsum extraction. This material was chosen on the basis of pilot experiments (Ballesteros et al., 2012, 2014). The design of the experimental slopes (Figure 1) included three factors: slope (1), aspect (2) and treatment (3). We considered: (1) two slopes: steep slopes (60-65 %, limited by the angle of rest of the spoil material) and shallow slopes (10-15 %, typical slopes left after quarrying, according to the quarry management plan) in combination with (2) two aspects: north- and south-oriented. In each of these 4 slope x aspect combinations we set up eight experimental plots (steep slopes = 5 x 10 m; shallow slopes = 5 x 20 m) and applied (3) three hydroseeding treatments and one control randomly to each of two replicate plots. The hydroseeding treatments were: (a) Paper cellulose (PC), consisting of water, seeds, paper cellulose mulch (200 $g\cdot m^{-2}$), soil stabiliser (0.5-0.8 % by mulch weight) and fertilizer (30 $g\cdot m^{-2}$ NPK 15-10-10 + 3MgO + 6S); (b) Paper cellulose + blanket (PCB), equal to PC but also covered with a straw and coir fibre blanket; (c) Wood fibre (WF), equal to PC, but mulch consisted of wood fibre (220 $g\cdot m^{-2}$), and (d) control (C), where no hydroseeding was applied. This provided 2 slopes angles x 2 aspects x 4 treatments x 2 replicates = 32 plots.

Hydroseeding was conducted in December 2011. The substrate was previously tilled to 10 cm depth to aid seed establishment. We used a mixture of native seeds (655 seeds/m^2) consisting of 47% gypsophiles and 53% gypsovags. Based on pilot experiments (Ballesteros *et al*. 2012), seeds of all taxa were added at the following rates (seed m^{-2}): Gypsophiles included *H. squamatum* (180), *L. subulatum* (120), and *O. tridentata* subsp. *crassifolia* (10); and gypsovags, *S. tenacissima* (100), *R. officinalis* (45), *H. syriacum* (100), *T. zygis* subsp. *gracilis* (50) and *T. capitatum* subsp. *gracillimum* (50). Seeds were collected from natural vegetation patches within the study area between June and September 2011.

2.4. Vegetation sampling

We sampled plant species composition and cover 2.8 years later (October 2014). Sampling in this season ensures to record late-emerging seedlings of target species (as observed in Ballesteros et al. 2012). We placed 4 equidistant linear transects along each of the 32 plots, and assessed three contact points every 0.5 m: at the centre and 0.5 m to each side of the transect (123 and 63 points per transect for shallow and steep slopes respectively). We recorded the perennial plant species occurring (i.e. chamaephytes and hemicryptophytes) plus bare soil, and calculated their cover as the proportion of points intercepted.

2.5. Data analyses

Canonical correspondence analysis (CCA) was performed to relate species composition to the explanatory variables (following Oksanen, 2015) using the "vegan" package (Oksanen et al., 2016). The species dataset was reduced by omitting the less frequent species (<5% of transects). Vegetation cover data were arcsin transformed before analyses (Crawley, 2007). Constraining variables (hydroseeding treatment, slope and aspect) were included in the model using forward selection based on the use of the AIC statistic as the selection criterion (Oksanen, 2015), with significance assessed using 200 permutations. Standard deviational ellipses (95% confidence limits) were used to illustrate the area covered by the hydroseeding treatments in the biplot. We also tested the relative influence of the explanatory variables (treatment, slope and aspect) on plant composition using the "adonis" function in the "vegan" package (Oksanen et al., 2016).

We analysed the effects of hydroseeding treatment, slope (shallow versus steep), aspect (north versus south) and their interaction on the cover of target species, gypsophiles separately, non-target species (i.e. other than sown gypsophiles and gypsovags), and total species. These effects were assessed fitting generalised linear mixed models (GLMMs) using treatment, slope and aspect as fixed factors and plot as random factor. Models were fitted applying the Laplace approximation of likelihood (Bolker et al., 2009), a Poisson error distribution and log-link function using the R "lme4" package (Bates et al., 2015). Similarly, we assessed the effects of treatment and its interaction with slope or aspect as fixed factors using aspect and slope respectively as random factors, and performing multiple comparisons with the R "multcomp" package (Hothorn et al., 2008). All statistical analyses were performed using R version 3.2.3 (R Core Team, 2015).

3. Results

3.1. Species composition

We recorded 28 perennial species in the plots. The mean number of species was greater in all hydroseeded treatments; mean values (±SE) were: PCB: 10.8±0.6, WF: 10.2±0.6, PC: 9.7±0.6, and C: 6.6±0.6. The most frequent species on the hydroseeded plots were *Lolium perenne* (94.8% of transects), *T. zygis* (89.6%), *R. officinalis* (81.3%), *Moricandia arvensis* (79.2%), *Medicago sativa* (76%), *Picnomon acarna* (74%), *H. squamatum* (70.8%), *O. tridentata* (70.8%), *L. subulatum* (67.7%), *H. syriacum* (62.5%), *T. capitatum* (50%) and *S. tenacissima* (37.5%). Frequency for all these species was always lower in control plots except for *M. arvensis* (93.8%) *and P. acarna* (75%) and other non-target species (e.g. *Lactuca serriola*, 53.1%, *P. miliaceum*, 28.1%, *Dittrichia viscosa*, 25%, *Ulex parviflorus*, 18.8%).

In the multivariate analysis, all explanatory variables were included in the model after forward selection in CCA reducing the AIC of the null model from 179.96 to 154.57; the resultant model was significant ($p < 0.001$). The constrained inertia within this CCA was 0.70 (37% of explained variance) and eigenvalues for the first five axis $\lambda_1 = 0.20$, $\lambda_2 = 0.14$, $\lambda_3 = 0.09$, $\lambda_4 = 0.08$ and $\lambda_5 = 0.05$. Hydroseeding treatment was the main factor in explaining species composition ($R^2 = 0.24$, $F = 18.96$, p-value = 0.001) followed by slope ($R^2 = 0.08$, $F = 19.22$, p-value = 0.001) and aspect ($R^2 = 0.07$, $F = 16.43$, p-value = 0.001). There were marked compositional differences between hydroseeded and control plots. The species plot (Figure 2) showed target species on the right of the ordination next to *L. perenne* and *M. sativa*. The hydroseeding treatments occupied a similar region on the right hand side of the ordination space overlapping near the origin because of the presence of the target species. The hydroseeding treatments shared all target species, except for paper cellulose that did not contain *L. subulatum* and *S. tenacissima.* Early-successional non-target species like *P. acarna* and *D. viscosa* were characteristic of PCB and PC, and *P. miliaceum* was only characteristic of PC. The control treatment was separated on the left hand side of the ordination and was related to *L. serriola*. Species such as *M. arvensis* and *Reseda stricta* occupied an intermediate position between the hydroseeding treatments and the control. Target species were associated to the southern aspects and shallow slopes (except *O. tridentata*).

3.2. Species cover

The dominant species according to their cover on the hydroseeded plots were the non-target species *L. perenne* (12.5%), *M. arvensis* (9.6%), *M. sativa* (6.3%), followed by the target species *T. zygis* (4.8%), *R. officinalis* (4.6%), *H. squamatum* (4.3%) in this order. Values for the remaining target species were *L. subulatum* (2.4%), *O. tridentata* (2.1%), *T. capitatum* (0.9%) and *S. tenacissima* (0.8%). The cover of non-target species was greater on control plots, where *M. arvensis* was the dominant species (34.7%).

The cover of target species and gypsophiles showed a significant response to hydroseeding treatment, slope and aspect, but not their interaction (Table 1). The target species cover was greatest on WF (28.2 out of a total cover of 61.1%), followed by PCB (21.7 out of 66.6%), PC (16.4 out of 59.5%) and C (3.8 out of 55.5%), with all treatments differing significantly (Figure 3A and D). In the case of gypsophiles, there were significant differences between treatments except for PC and PCB (Figure 3B). Target species cover was always greater on the shallow slopes (Figure 3E) and southern aspect (Figure 3I) when comparing hydroseeding treatments to their counterpart. The same was true for gypsophiles (Figure 3F and J). Target species showed no differences in the control treatment either among slopes or aspects (Figure 3E and F), as also occurred for gypsophiles (Figure 3I and J). The results were supported by the individual response of target species, except for *O. tridentata* that performed better on the northern slope. The best treatment for most target species was WF, excepting *R. officinalis* and *T. capitatum* that performed better in PCB (Figure S1; Figure S2).

The cover of non-target species (mainly early-successional colonizers) was affected by hydroseeding treatment and the interaction of slope with aspect (Table 1). Cover was greatest on control plots and the lowest on WF (Figure 3C). The C treatment had its maximum on shallow slopes and southern aspects, where WF reached its minimum (Figure 3G and K).

Total plant cover showed a significant response to slope and slope by aspect interaction (Table 1). There were significant differences between treatments, with the greatest total plant cover in PCB, followed by WF, PC and C (Figure 3D). These differences were due to different performance of treatments on the steep slopes, as they all had similar total cover on the shallow one (Figure 3H). Total cover was greater on the shallow slopes in C and PC compared to their counterparts on the steep slopes, whereas PCB and WF performed similarly on both inclinations (Figure 3H). Total cover was similar for all treatments in the two aspects, with greatest cover achieved in PCB on the southern slope (Figure 3L).

We observed marked differences in the cover and proportion of species between northern steep slopes and all other aspect and slope combinations, with the first showing a particular increase of non-target species cover at the expense of target species (Figure 4).

4. Discussion

Our findings show gypsicolous vegetation of high conservation value can be restored in quarry spoil slopes in the short term using standard hydroseeding methods. Natural succession has previously proved to have a limited potential for the restoration of gypsicolous vegetation in the short- to medium-term (<25 years; Martín et al. 2003; Mota et al., 2003, 2004; Dana & Mota, 2006; Ballesteros et al., 2012). Here, our results demonstrate hydroseeding ensures the establishment of target vegetation in the short-term, helping to jump-start succession and moving it towards the desired community.

The vegetation response was conditioned by the hydroseeding method, slope and site aspect. Hydroseeding method had the greatest effect on target vegetation. Target vegetation established better using wood fibre, paper mulch + blanket, or paper mulch than in the control treatment (in descending order). Restored and control plots differed remarkably. Hydroseeded plots had a more desirable species composition with greater target vegetation cover than control plots, which were almost completely occupied by non-target species typical of early-successional stages (i.e. colonizers). This was true despite other non-target species such as *L. perenne* and *M. sativa* being similarly abundant in the hydroseeded plots, probably because of seed remaining unintentionally in tanks from previous hydroseedings, thus explaining why these species were more frequent than in control plots.

Wood fibre was the most effective treatment for the establishment of target vegetation, specifically for gypsophile species. This treatment achieved the most similar cover to undisturbed gypsophilous vegetation for target species (28 vs ~30% respectively) and gypsophiles (16 vs ~22%); (calculated from Marchal et al. 2008), especially on shallow slopes, and south orientation. The improved results with wood fibre could be attributed to its capability of creating a thicker mat, holding seeds in place, resisting erosion more effectively than paper cellulose, or retaining more soil moisture thus creating a more favourable environment for target species seeds (Gruda, 2008; Profile, 2011). In addition, wood fibre not only produced the greatest target species cover but also the lowest cover of undesirable species, minimising the chances of potential competitors becoming dominant, and overall producing the greatest chance of favouring the recovery of the gypsicolous plant community.

The establishment of target species on paper mulch and paper mulch + blanket was less effective overall. On shallow slopes, both treatments produced similar results, but on steep ones paper mulch + blanket was better. This result was expected, given organic blankets are widely used to improve hydroseeding outcomes by retaining seeds and controlling erosion and run-off on steep slopes (e.g. Muzzi et al., 1997; Katritzidakis et al., 2007; Cohen-Fernández & Naeth, 2013).

The target vegetation performed better on shallow slopes in all hydroseeding treatments. Steep slopes are more prone to erosion and run-off (Kapolka & Dollhopf, 2001), and gravity allows seeds to be dragged downwards causing substantial seed losses (Cerdà & García-Fayos, 1997) hence limiting plant establishment (Matesanz et al., 2006; García-Fayos et al., 2010). These results are commonly found in other areas with variable slopes (e.g. roadsides and other mine wastes); in most cases steeper slopes perform worse than shallower ones (García-Fayos et al., 2010, Bochet et al., 2011).

Target vegetation produced a satisfactory response on shallow slopes in the two orientations and on steep northern slopes. The xerophytic and stress-tolerant nature of the target species allowed them to perform well in most situations, except steep slopes on northern aspects. This latter combination produced the worst results due to idiosyncratic effects that reduced considerably target vegetation cover in favour of non-target species. The lower insolation on steep, northern slopes appears to reduce water and physical limitations of gypsum substrates, allowing generalist vegetation (i.e. non-target species) to develop more readily (Pueyo & Alados, 2007) competing with the desired species of the target habitat (Pueyo et al., 2007). At this latitude, north-facing aspects receive less solar radiation, soil moisture is higher, and surface temperatures are generally more favourable for vegetation (Kutiel, 1992; Pueyo & Alados, 2007; Alday et al., 2010). This pattern has also been found on the vegetation on gypsum quarry landfills in SE Spain (Martín et al., 2003), where northern aspects had a much greater plant cover than southern aspects, although it did not seem to affect negatively the cover of gypsicolous species or gypsophiles as in our study. However, the identity of species and slope angles were not reported and hence direct comparisons are difficult. In turn, our results for the three gypsophile species agree those of Pueyo et al. (2007) with *H. squamatum* performing better in south oriented and shallow slopes, *L. subulatum* in both orientations, and *O. tridentata* in northern slopes. These results must be taken into account when designing the restoration plan, specifically for *O. tridentata* subp. *crassifolia*, endemic to the area and particularly affected by quarrying (Ballesteros et al. 2013). All the other target species generally performed better on southern aspects (exceptions being *T. zygis* and *T. capitatum* in wood fibre). On steep, southern slopes, target species as a whole performed similarly well as on shallow slopes, proving this harsher situation can also be restored by means of hydroseeding. Therefore, except on steep northern slopes, where non-target species become more competitive, our results showed target species can be established satisfactorily by hydroseeding.

The present study helps to guide decisions for the restoration of disturbed gypsum vegetation affected by quarrying. Figure 5 summarises an approach to treatment selection based on our results. The “no restoration” option led to the occurrence of early-successional species, slow succession and uncertain long term recovery. By contrast, this study demonstrates the short-term benefits of conducting hydroseeding early after disturbance. The effectiveness of measures was greater on shallow slopes where wood fibre produced the best results. Alternatively, paper mulch obtained reasonably good results, so the choice between the two methods can be based on the cost-benefit trade-off. On the other hand, the effectiveness of hydroseeding methods was affected strongly by steep slopes, and thus minimising them wherever possible would generally improve the restoration outcome. When this is not possible, designing stable slopes must be a priority, taking into account geomorphological principles and adequate drainage. If the erosion risk cannot be mitigated, application of organic blankets should help control erosion and run-off until a vegetation cover develops (Lorite et al., 2015). Conversely, in the absence of prominent erosion risks, wood fibre was the most effective and hence recommended measure. Our results showed gypsicolous target vegetation established reasonably well on steep southern slopes whereas non-target vegetation established better on steep northern slopes, at the expense of target species. The reduced environmental suitability of these areas combined with increasing competitive interactions suggest simple approaches such as increasing the seed supply would not be cost-effective in very steep, northern slopes. In this case, the extension of northern steep slopes in the global project must be taken into account to assess whether they could be managed with less ambitious goals (e.g. slope stabilisation with non-specific target species) or, if the recovery of gypsicolous vegetation was imperative, additional and costly site-specific actions will probably be required such as planting schemes (Ballesteros et al., 2014).

The cost-effectiveness of each approach must be borne in mind when planning restoration programs. Contouring of the slopes should be carefully planned in advance to minimise overall costs. The treatments tested differ strongly in economic terms. The least costly was paper mulch (0.56 €/m^2), followed by wood fibre (0.72 €/m^2) and paper mulch + blanket (3.17 €/m^2). Although paper mulch showed limited results in steep slopes, this option could be considered for shallow slopes, given it can be very helpful to restore target vegetation at large scale at a low price provided favourable topography. The most effective option was wood fibre, with the best performance in both shallow and steep slopes for only a narrow cost increase compared to that of paper mulch hydroseeding. Being more expensive, paper mulch + blanket could be considered with an additional focus in increasing slope stability in very steep slopes. In this sense, the treatment application should be site-specific to minimise costs and optimise their performance

5. Conclusions

Our results prove the establishment of gypsicolous vegetation can be achieved in disturbed quarry slopes by conventional hydroseeding methods in the short-term. All hydroseeding treatments were useful for ecological restoration of the target vegetation. However, the success of the intervention was strongly conditioned by the slope, with more limited results achieved in steep slopes. The most satisfactory results were obtained using wood fibre mulch with the greatest establishment of gypsicolous vegetation on shallow slopes. Comparable results were only attained by the paper cellulose + blanket treatment on the steep slopes. In spite of being more expensive, the wood fibre mulch treatment could be considered for its additional applicability to prevent erosion problems and improve slope stability. However, wood fibre or paper cellulose mulches should be preferred in moderate slopes given the lower-cost, easy application and greater ecological benefits of these options. This experiment should be monitored over the long term to evaluate the ecological, technical and economic viability of the tested hydroseeding methods and confirm their applicability to achieve effective large scale restoration of gypsum disturbed environments. The knowledge derived from this study will help to develop future programs for the management of gypsum habitats.

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Supporting Information

Table S1. Mean values (± SD) of the physicochemical characterization of the gypsum spoil used.

Figure S1. Cover (%) of target species (mean±SE) by treatment and slope.

Figure S2. Cover (%) of target species (mean±SE) by treatment and aspect.

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Table 1. Results of generalised linear mixed models (GLMMs) testing the effects of hydroseeding treatment, slope, aspect and their interaction on the cover of target species, gypsophiles separately, non-target species, and total plant species. The chi-square statistic (χ^2) of the fixed factors and their significance are presented. All results with p<0.05 are in bold.

		Species cover							
		Target species		Gypsophiles		Non-target species		Total	
	df	χ^2	p	χ^2	p	χ^2	p	χ^2	p
Treatment (T)	3	30.29	**<0.001**	36.60	**<0.001**	10.97	**0.012**	2.88	0.410
Slope (S)	1	7.38	**0.007**	6.01	**0.014**	0.61	0.434	6.54	**0.011**
Aspect (A)	1	8.45	**0.004**	4.45	**0.035**	0.79	0.374	1.55	0.213
T × S	3	2.45	0.484	2.88	0.410	4.74	0.192	1.86	0.602
T × A	3	4.91	0.178	2.78	0.427	1.51	0.681	0.92	0.820
S × A	1	1.79	0.180	2.40	0.121	12.13	**<0.001**	4.33	**0.037**
T × S × A	3	4.69	0.196	7.69	0.053	0.27	0.965	2.85	0.415

Table S1. Mean values (± SD) of the physicochemical characterization of the gypsum spoil used. Twelve gypsum spoil samples were randomly collected in the study site at 0-30 cm depth in order to evaluate the main properties that might have influenced species response in our study. N is the number of samples used for analyses. Analyses were conducted following the methodology in Mañares et al. (1998) and MAPA (1994). [a] Exchangeable cations.

Variable	N	Gypsum spoil
Gravel (>2mm) (%)	4	33.48 ± 3.78
Sand (2-0.05 mm) (%)	12	8.99 ± 2.17
Coarse silt (0.05-0.02 mm) (%)	12	9.60 ± 6.22
Fine silt (0.02 mm) (%)	12	41.44 ± 7.60
Clay (<0.02 mm) (%)	12	39.97 ± 8.22
pH	12	7.79 ± 0.04
Cation exchange capacity ($cmol_+$/kg)	12	8.15 ± 1.77
Ca^{2+} ($cmol_+$/kg)[a]	12	7.68 ± 1.83
Mg^{2+} ($cmol_+$/kg)[a]	12	0.22 ± 0.06
Na^{+} ($cmol_+$/kg)[a]	12	0.04 ± 0.01
K^{+} ($cmol_+$/kg)[a]	12	0.20 ± 0.07
Total carbon (%)	12	3.26 ± 0.45
Inorganic carbon (%)	12	3.27 ± 0.42
Organic carbon (%)	7	0.04 ± 0.03
Total N (%)	12	0.029 ± 0.005
$CaCO_3$ (%)	12	27.25 ± 3.52
Gypsum (%)	12	47.96 ± 28.22
Electrical conductivity (dS/·m)	12	2.27 ± 0.01
Water retention at field capacity (%)	8	31.09 ± 1.18
Water retention at wilting point (%)	8	20.98 ± 0.96
Available-water content (%)	8	10.11 ± 1.01

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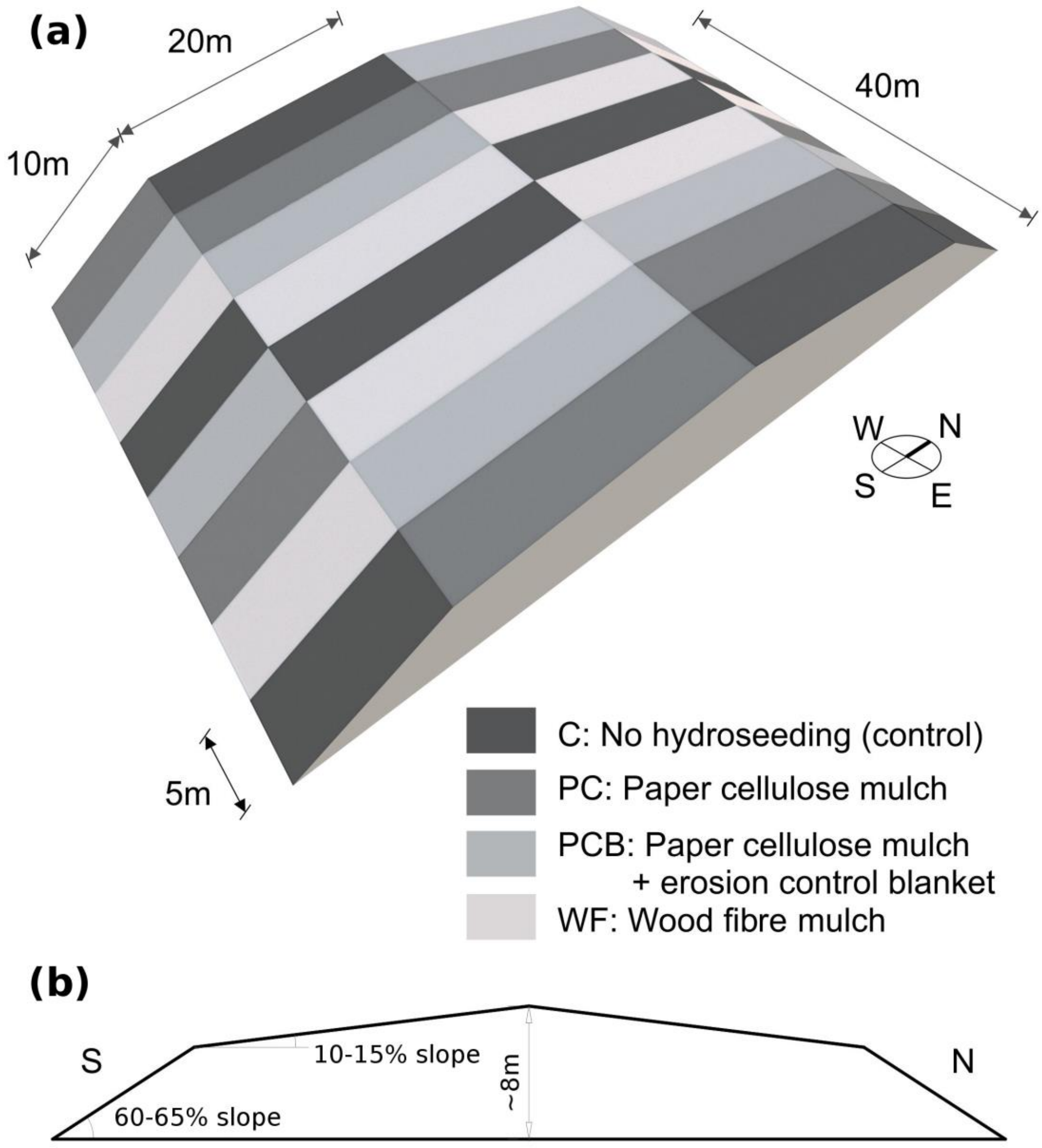

Figure 1. (a) Schematic of the experimental slopes showing the hydroseeding treatments distributed on two contrasting slopes: shallow (10-15%) and steep (60-65%); and two aspects: north (N) and south (S). (b) Cross section of the experimental slopes. The space between the plots is not represented.

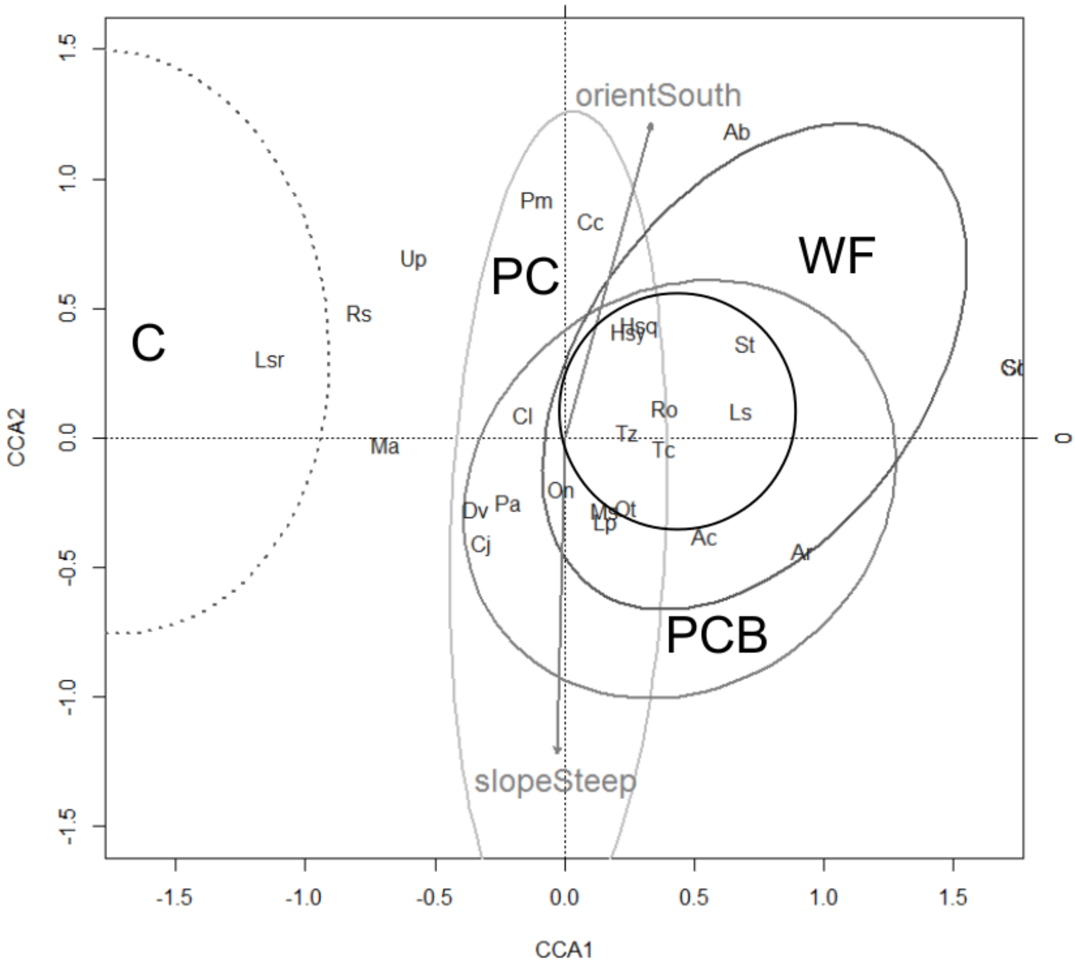

Figure 2. Constrained CCA ordination plot of treatments of the species cover 2.8 years after hydroseeding at the experimental area in Escúzar, Granada, SE Spain; the ordination was constrained on hydroseeding treatment. The SD ellipses (95% confidence limits) of transects position by treatment are shown. **Treatments:** C: control; PC: hydroseeding with paper cellulose mulch; PCB: hydroseeding with cellulose mulch plus erosion control blanket; WF: hydroseeding with wood fibre mulch. Treatments were tested on two contrasting slopes**:** shallow (10-15%) and steep (60-65%); and two aspects: north and south. **Species:** Target species are highlighted with a black circle. Ab = *Artemisia barrelieri*, Ac = *Anthyllis cytisoides*, Ar = *Andryala ragusina*, Cc = *Centaurea calcitrapa*, Cj = *Chondrilla juncea*, Cl = *Carthamus lanatus*, Col = *Colutea arborescens*, Dv = *Dittrichia viscosa*, Hsq = *Helianthemum squamatum*, Hsy = *Helianthemum syriacum*, Lp = *Lolium perenne*, Ls = *Lepidium subulatum*, Lsr = *Lactuca serriola*, Ma = *Moricandia arvensis*, Ms = *Medicago sativa*, On = *Onopodum nervosum*, Ot = *Ononis tridentata* subsp. c*rassifolia*, Pa = *Picnomon acarna*, Pm = *Piptatherum miliaceum*, Ro = *Rosmarinus officinalis*, Rs = *Reseda stricta*, Sh = *Scolymus hispanicus*, St = *Stipa tenacissima*, Tc = *Teucrium capitatum* subsp. *gracillimum*, Tz = *Thymus zygis* subsp. g*racilis,* Up= *Ulex parviflorus*.

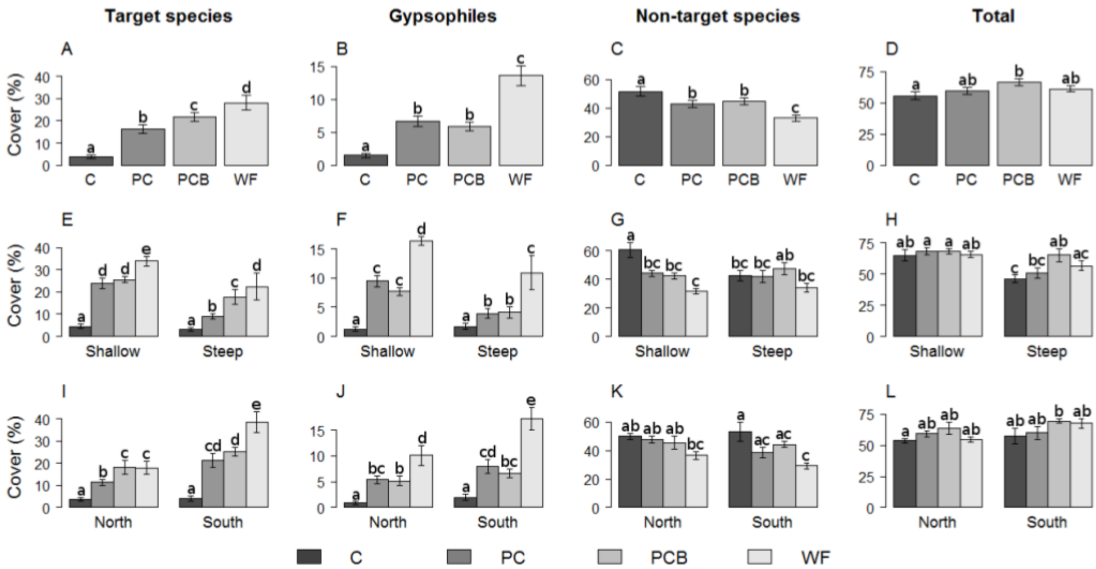

Figure 3. Cover (%) of target species, gypsophiles separately, other occurring non-target species and total plant cover by treatment (A-D), and the combinations of treatment and slope (E-H), and treatment and aspect (I-L). Hydroseeding treatments: C: No restoration (no hydroseeding); PC: paper cellulose mulch; PCB: paper cellulose mulch plus an erosion control blanket; and WF: wood fibre mulch.

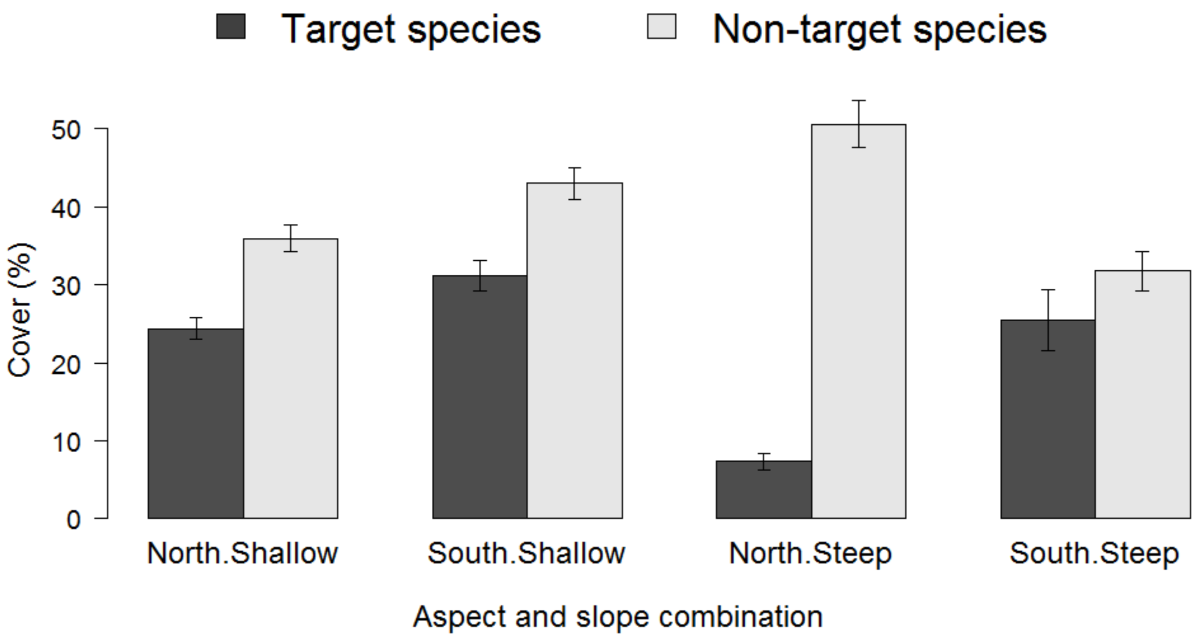

Figure 4. Cover (%) of target and non-target species (mean±SE) by aspect and slope combination showing idiosyncratic effects on north steep slopes (hydroseeding treatments are pooled together, control treatment is not included).

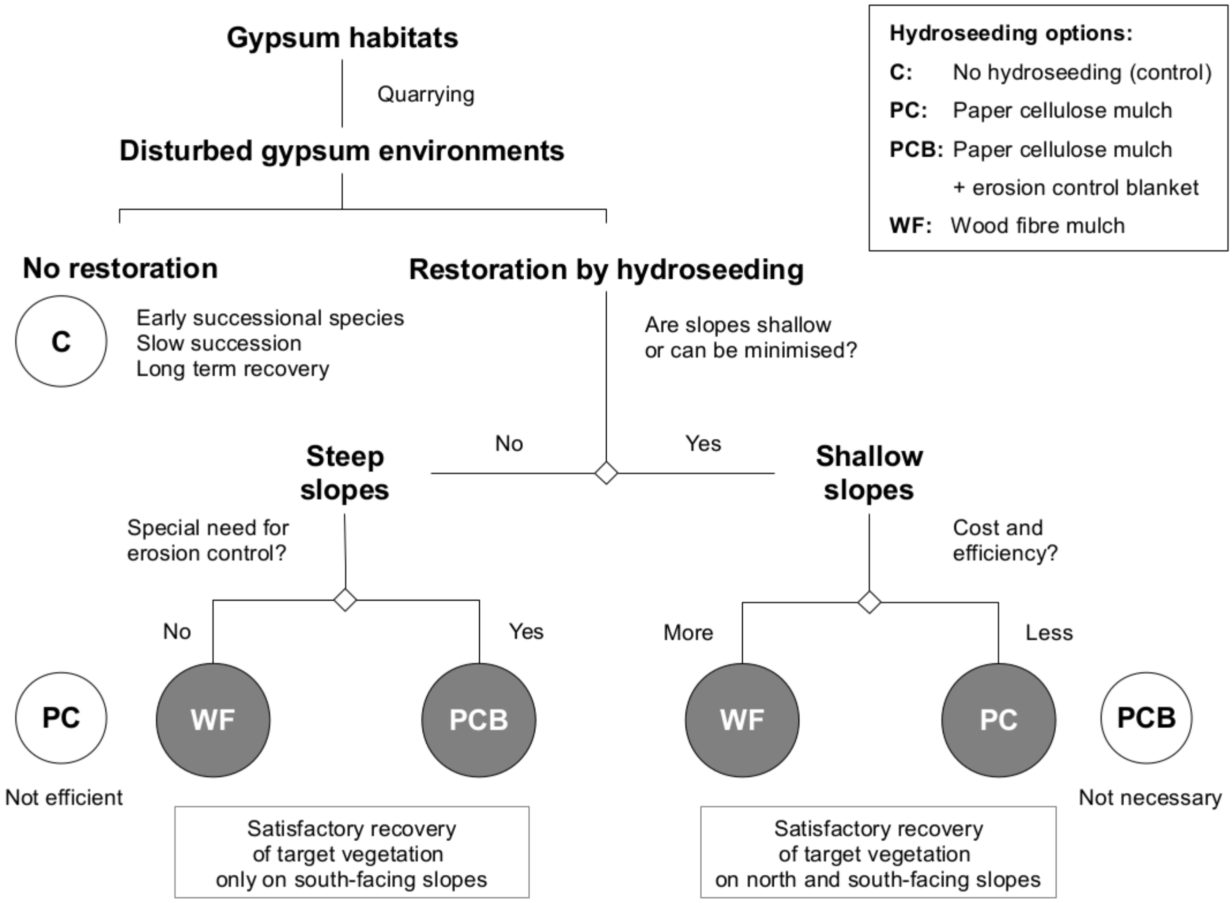

Figure 5. Decision pathways for the selection of hydroseeding methods to restore gypsum vegetation on quarry slopes according to our results.

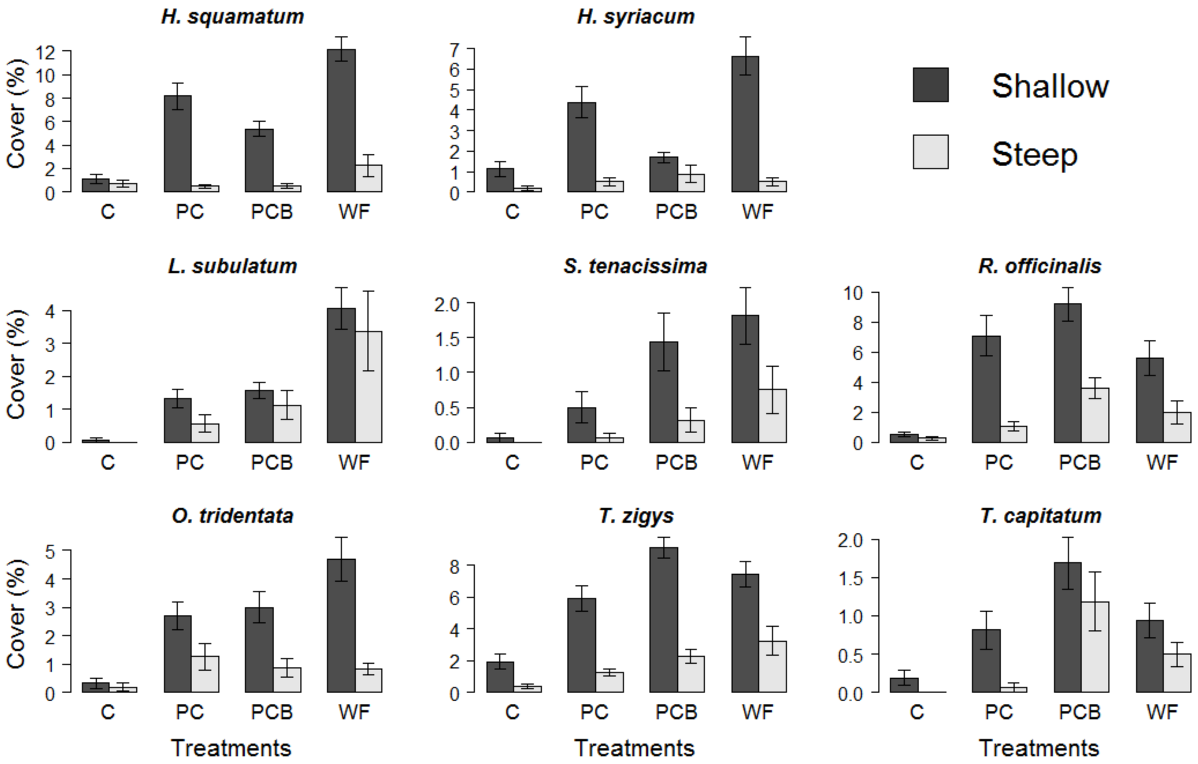

Figure S1. Cover (%) of target species (mean±SE) by treatment and slope (north- and south-facing slopes are pooled together). Hydroseeding treatments: C: No restoration (no hydroseeding); PC: paper cellulose mulch; PCB: paper cellulose mulch plus an erosion control blanket; and WF: wood fibre mulch. Slope inclination: shallow (10-15%) and steep (60-65%).

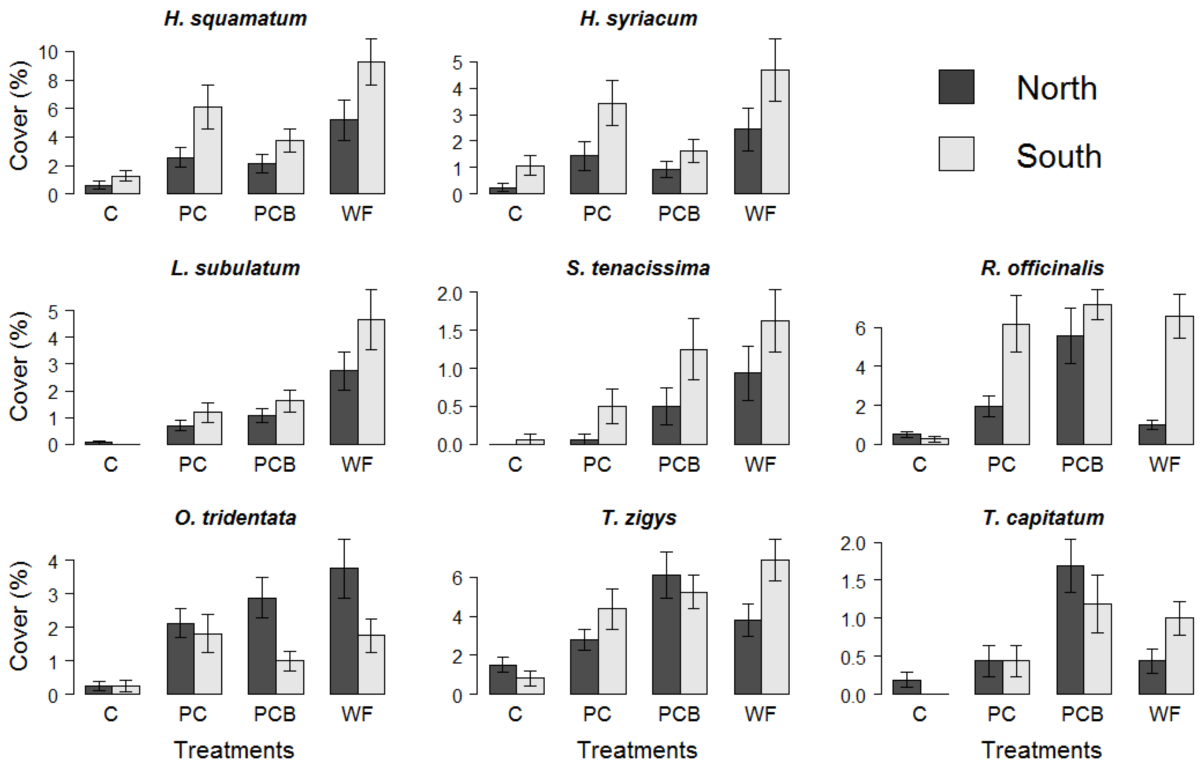

Figure S2. Cover (%) of target species (mean±SE) by treatment and aspect (shallow and steep slopes are pooled together). Hydroseeding treatments: C: No restoration (no hydroseeding); PC: paper cellulose mulch; PCB: paper cellulose mulch plus an erosion control blanket; WF: wood fibre mulch.