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Central role of bedding materials for gypsum-quarry restoration: An experimental planting of gypsophile species

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ABSTRACT

The loss of the original soil and mineral resources caused by quarrying activities represents a major challenge for the restoration of singular flora associated with specific substrates. In particular, the rare and original gypsum flora is severely affected by quarrying, and identifying the best measures to recover it is decisive for its conservation. In this paper, we evaluate the efficacy that planting with several contrasting bedding-materials has for the recovery of three native gypsophile species in gypsum habitats affected by quarrying. With this aim, in a affected gypsum area in SE Spain, we experimentally planted one-year-old nursery-grown plants of *Helianthemum squamatum*, *Lepidium subulatum*, and *Ononis tridentata* subsp. *crassifolia*, employing four bedding materials potentially useful for restoration: raw gypsum, gypsum spoil, topsoil on gypsum spoil, and marls. Plant performance was evaluated in terms of survival, growth, and the production of flowers, fruits, and seeds. High survival was achieved in all the treatments, demonstrating the excellent response of these species to planting. However, bedding materials had a significant effect on plant performance, with raw gypsum and gypsum spoil being the options that most benefited growth and production (in terms of flowers, fruits, and seeds). Remarkable results were achieved in raw gypsum, although gypsum spoil appears to be the most reasonable option for restoration, given its low cost, wide availability, and potential to recover disturbed gypsum environments. By contrast, common measures such as the use of topsoil should not be routinely recommended for the recovery of gypsum vegetation. Hence, our study shows the importance of identifying the most appropriate measures when specialized flora is the object of restoration and thus will contribute to the development of strategies for the conservation of gypsum habitats affected by quarrying.

1. Introduction

Restoration of the native vegetation in mining areas usually poses a major problem due to several limitations, with soil loss and the alteration of the original topography being some of the most drastic disturbances (Bradshaw and Chadwick, 1980; Clemente et al., 2004). Consequently, additional substrates are required when the recovery of the former plant community is the goal of restoration (Oliveira et al., 2011). Common practices include the use of raw spoils generated by mining to backfill the disturbed area (Carrick and Krüger, 2007). These materials are often regarded as difficult substrates for vegetation recovery due to several limiting factors, such as low nutrient content or poor structure (Singh et al., 2002). Thus, the application of the topsoil retrieved from the pre-mined area and/or the addition of organic amendments to the spoil are widely used to overcome these limitations (Ghose, 2004; Kundu and Ghose, 1994; Martínez-Ruiz and Fernández-Santos, 2005). However, severe changes in the original soil properties may result in contrasting situations for plant development. While the use of raw spoil may constitute a harsh environment and slow down plant-cover regeneration (Alday et al., 2011), the use of topsoil or amendments may promote the establishment of undesirable species (e.g. generalist-colonizers) at the expense of the native vegetation, and consequently hinder the restoration of the former habitat (Ballesteros et al., 2012; Castillejo and Castelló, 2010; Nair et al., 2000). In this context, the selection of starting materials determines the success of restoration processes (Bradshaw, 2000), and is particularly decisive for the recovery of singular flora

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associated to specific substrates, as reported for copper, serpentine or gypsum soils (Ballesteros et al., 2012; O'Dell and Claassen, 2009; Whiting et al., 2004).

Specifically gypsum areas, which harbor rare and original flora worldwide (Escudero et al., 1999; Meyer, 1986; Parsons, 1976), are often affected by quarrying and represent a major challenge in the restoration of disturbed singular environments (Mota et al., 2011). In this context, previous works have demonstrated the limitations that natural succession has for the recovery of gypsum vegetation over the short or middle term (e.g. Ballesteros et al., 2012; Dana and Mota, 2006; Mota et al., 2003, 2004). Thus, several studies have based their approach on the management of substrates and species in accordance with the restoration goals. In this sense, previous works in arid gypsum areas have reported satisfactory revegetation with environment-adapted species planted on byproducts (e.g. spoil or tailings) from gypsum mining (Blignaut and Milton, 2005; Rao and Tarafdar, 1998; Sharma et al., 2001). Other works in Mediterranean areas have approached the rehabilitation of disturbed gypsum soils by applying topsoil and/or organic amendments, showing that the establishment of undesirable vegetation can hinder the restoration of native gypsophile species (Ballesteros et al., 2012; Castillejo and Castelló, 2010; Marqués et al., 2005). Moreover, the study of the short-term response of sowing native gypsophile species under several bedding materials and soil surface treatments have demonstrated that the measures applied may strongly influence the restoration process (Ballesteros et al., 2012).

Identifying the best restoration techniques is crucial to recover gypsum vegetation. In particular, the Iberian gypsum vegetation is severely affected since Spain is one of the main gypsum producers worldwide (Craig et al., 2007). Despite that gypsum habitats are considered a priority for conservation at the European level (Anonymous, 1992), large areas are disturbed, affecting the singular local flora (e.g. Ballesteros et al., 2012, 2013; Mota et al., 2004). Consequently, there is a need to develop specific measures to restore these environments. In this sense, the recovery of the flora has mostly been approached relying on unaided natural succession (Dana and Mota, 2006; Mota et al., 2003, 2004), or using active restoration techniques such as hydroseeding (Matesanz and Valladares, 2007) or sowing (Ballesteros et al., 2012). Sowing may constitute an advantageous method in restoration projects. Under ideal conditions, it could be useful to provide high plant density and cover in a natural-like distribution at a lower cost than planting. By contrast, planting can provide more efficient seed use, more resistant plants and faster establishment at the expense of increasing propagation and planting labor costs. However, although previous works have reported the benefits of planting in disturbed quarry areas (Singh et al., 2002), and specifically for species inhabiting gypsum environments (Blignaut and Milton, 2005; Sharma et al., 2001), there is no scientific literature available that tests the applicability of planting for the restoration of gypsum specialists.

Therefore, given the importance of substrates and species, the aim of this study is to improve the restoration of Iberian gypsum habitats affected by quarrying by (1) testing the applicability of planting as a method to establish three characteristic gypsophile species and (2) identifying the bedding materials that maximize plant performance.

2. Material and methods

2.1. Site description

The study was performed in an experimental area set on a cereal old field consisting of marls next to an active quarry in Escúzar (Granada, SE Spain; 37°2′ N, 3°45′ W) at 950 m asl. The climate type 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 421.1 mm, occurring mainly in winter. The area is in the Neogene sedimentary basin of Granada, the dominant substrates being lime and gypsum from the late Miocene, the latter in combination with marls (Aldaya et al., 1980). The predominant soils in the gypsum outcrops are gypsisols (Aguilar et al., 1992). The vegetation of the area is a mosaic of fields with crops and orchards (cereals and almond and olive trees) and scattered patches of native plants growing over gypsum outcrops. The native vegetation is included in the Habitat Directive as 1520, "Iberian gypsum vegetation, *Gypsophiletalia*" (Escudero, 2009), and is characterized by plants exclusive to gypsum soils (gypsophiles), such as *Helianthemum squamatum* (L.) Dum. Cours., *Lepidium subulatum* L. or *Ononis tridentata* subsp. *crassifolia* (Dufour ex Boiss.) Nyman. In addition, there are also other frequent non-exclusive species of gypsum substrates such as *Stipa tenacissima* L., *Rosmarinus officinalis* L., *Helianthemum syriacum* (Jacq.) Dum. Cours. and *Thymus zygis* L. subsp. *gracilis* (Boiss.) R. Morales (according Marchal et al., 2008).

2.2. Target species

Three characteristic species of the gypsum habitat were selected for experimental planting including: *H. squamatum* (*Cistaceae*) and *L. subulatum* (*Brassicaceae*), both widely distributed in gypsum outcrops in the Iberian Peninsula and some localities in North Africa (see Mota et al., 2011), and *O. tridentata* subsp. *crassifolia* (*Leguminosae*), a narrow endemic restricted to gypsum outcrops in SE Spain (CW Granada province) and considered under threat (Vulnerable, VU, according to Ballesteros et al., 2013).

2.3. Field experiment

Four materials reproducing potential options for plant reintroduction that mimicked possible post-quarrying conditions were set up in the experimental area (see Ballesteros et al., 2012). The bedding materials included: (1) marls (M), using the substrate in the area to recreate a scenario where gypsum rock had been completely eliminated, and where the old-field topsoil (c. 30 cm) and thus its seed bank had been removed; (2) gypsum spoil (GS), providing a layer of gypsum mine spoil (0.5 m) generated from gypsum quarrying; (3) topsoil (T), placing a layer of topsoil (ca. 10 cm) retrieved from the natural habitat (after 8 months of stockpiled storage), on top of a gypsum spoil layer (0.5 m); and (4) raw gypsum (RG), consisting of a layer (0.5 m) of coarse gypsum. While raw gypsum is the material used for industrial processing, gypsum spoil is a byproduct with no commercial value generated during the quarrying. Supplementary information on the properties of the materials and the moisture content are provided in Appendix A and B, respectively.

In February 2011, we planted on each material one-year-old nursery-grown plants of *H. squamatum* (50 ind. × 4 bedding treatments = 200 individuals), *L. subulatum* (50 ind. × 4 bedding treatments = 200 individuals), and *O. tridentata* subsp. *crassifolia* (33 ind. × 3 bedding treatments = 99 individuals). Due to the low plant availability of the latter species, we ruled out planting in the marls treatment, for being considered a priori the least suitable for restoration. Plants were set 0.75 m apart. The spontaneous flora was eliminated by clipping aboveground biomass in all materials in February 2011 and April 2012 to reduce potential competition from other species. Plants were produced in a nursery, using

250 cm^3 plastic pots filled with a mixture of commercial substrate (organic matter = 85.4%, pH 6–7, N 260 mg kg^{-1}, P 389 mg kg^{-1}, K 2000 mg kg^{-1}, Mg 678 mg kg^{-1}, Fe 15 mg kg^{-1}) and gypsum in proportions of 75 and 25%, respectively. All plants were obtained from seeds manually harvested in patches of natural vegetation in the study area between June and September 2009.

To evaluate species performance with respect to bedding material, we monitored the survival of each individual on a monthly basis from February 2011 to June 2012. In addition, plant growth was estimated by measuring differences in plant volume between three sampling dates (July 2011, April 2012 and June 2012), using the equation for the volume of a semispheroid [$V = (4/3\,\pi\,r^2\,h)/2$], where r is the plant radius and h is the plant height (Lorite et al., 2010). Flower production was estimated by counting the flowers in three randomly taken flowering stems per plant at flowering peak (June 2012). Afterwards, the flower average was multiplied by the number of flowering stems per plant to estimate the number of flowers per plant. Fruit production was estimated following the same procedure at peak fruiting (July 2012). Seed output was estimated by counting well-formed seeds in 10 fruits from 30 plants per species and treatment (10 fruits × 30 plants per species × bedding material; 1200 fruits, respectively, for *L. subulatum* and *H. squamatum*, and 900 fruits for *O. tridentata* subsp. *crassifolia*). Seed production per individual was calculated by multiplying its fruit yield by average seed set for each species.

2.4. Statistical analysis

The effect of bedding treatment on overall species mortality and global growth over time was modeled fitting Generalized Linear Mixed Models (GLMMs), including bedding material as a fixed factor and species as a random factor. In particular, mortality was modeled using the "lmer" function, (R "lme4" package; Bates et al., 2013), specifying a binomial error distribution and logit-link function. Survival differences between bedding materials were assessed for each species using Kaplan–Meier survival curves (R "survival" package; Therneau, 2013). Plant growth was modeled, using the "lme" function (R "nlme" package; Pinheiro et al., 2013). Model parameters were estimated using the Laplace approximation of likelihood (Bolker et al., 2009). To evaluate the effect of bedding treatment by species on plant growth, production of flowers, fruits, and seeds, and on the average seed production per fruit, we fitted Generalized Linear Models (GLMs), assuming a Poisson error distribution and log-link function. Multiple comparisons were made in all analyses using the R "multcomp" package (Hothorn et al., 2008).

Table 1
Effect of bedding treatment on overall plant survival, considering all species, evaluated fitting a Generalized Linear Mixed Model (GLMM). Bedding treatment, as fixed factor and species as random factor. Random effects are expressed in the last row of the table.

Survival	Estimate	SE	z value	Pr(>|z|)
Intercept	2.7352	0.8925	3.065	0.00218
Raw gypsum	−0.0816	0.4034	−0.202	0.83978
Topsoil	−0.8055	0.3742	−2.153	0.03132
Marls[a]	0.8640	0.5263	1.642	0.10068
Random effects	Variance: 2.04		SD: 1.428	

[a] The marls treatment was not applied to *Ononis tridentata* subsp. *crassifolia*.

3. Results

3.1. Survival

Overall survival over the first 17 months (February 2011–June 2012), considering all species and bedding treatments was 87.2%, with the highest survival in marls (94%), followed by gypsum spoil (88.7%), raw gypsum (88%) and topsoil (79.7%). Despite the high overall survival, significantly more deaths occurred in topsoil (Table 1). This was mainly due to *H. squamatum*, which showed significantly lower survival in this treatment, since no differences were found for *L. subulatum* or *O. tridentata* subsp. *crassifolia* when the effect of the bedding-materials was compared within species (Fig. 1).

3.2. Growth

Bedding material significantly affected overall plant growth when all species were considered together (Fig. 2a and Table 2). Significant differences were found between treatments in each sample period (Table 2). The first volume measures taken in July 2011 showed significant positive effect only in gypsum spoil. Nevertheless, measures taken in April 2012 and June 2012 showed

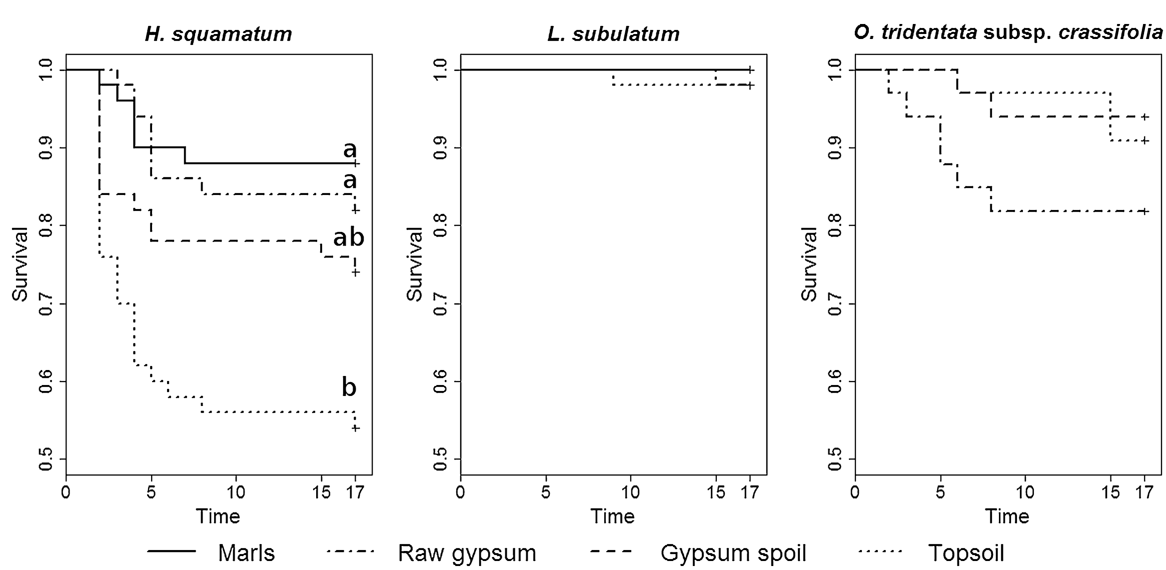

Fig. 1. Kaplan–Meier survival curves representing species survival over time (from February 2011 to June 2012) for each bedding material. Different letters represent statistically significant differences between groups ($p < 0.05$).

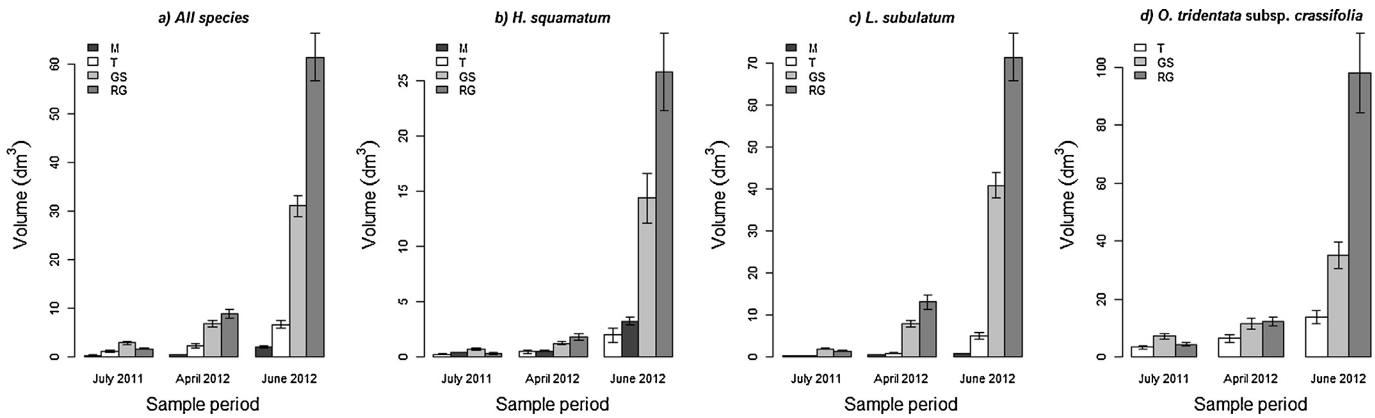

Fig. 2. Plant volume (mean ± SE) of the three species assayed measured in three sample periods (July 2011, April 2012, and June 2012) for each bedding material: M, marls; T, topsoil; GS, gypsum spoil; RG, raw gypsum.

significant positive effects in both gypsum spoil and raw gypsum treatments, with the highest overall plant growth under the raw gypsum treatment. This pattern recurred in all species individually (Fig. 2bcd, and Table 3 expressing the last measures taken in June 2012). In the other treatments, plants had significantly lower growth, the lowest being in the marls for *L. subulatum*, and in topsoil for *H. squamatum* and *O. tridentata* subsp. *crassifolia* (Fig. 2bcd).

3.3. Flower, fruit, and seed production

Bedding materials had significant effects on flower, fruit, and seed production in all species (Table 3). Flower and fruit production differed significantly between all treatments, proving higher in raw gypsum for all species, followed by gypsum spoil. Comparing marls and topsoil treatments (the overall worst treatments), *H. squamatum* produced more flowers and fruits in marls, while the opposite was true of *L. subulatum*, which performed better in topsoil. *O. tridentata* subsp. *crassifolia*, registered the worst results for topsoil. Fruits yielded similar seed sets within species among treatments, except for *H. squamatum*, having more seeds per fruit in the gypsum spoil and less in topsoil. The number of seeds per plant also differed significantly between treatments, being the highest in raw gypsum and gypsum spoil for all species, followed by marls in *H. squamatum*, or topsoil in *L. subulatum* and *O. tridentata* subsp. *crassifolia*, (Table 3).

4. Discussion

The high survival rate found in our study, with 87.2% of plants alive at the end of the study period, suggests that planting on the tested bedding materials is an efficient technique to achieve good establishment for all the species. Thus, considering all species together, the response to each material proved very satisfactory, with survival rates as high as 79.7% in the worst case (topsoil). Species individually responded very favorably to planting, with good survival rates, except for significantly worse performance of *H. squamatum* in topsoil (54% survival). Similarly, moderate or good survival have been achieved in other species planted on degraded gypsum soils (i.e. ∼45% in Spain, Rincón et al., 2007) or gypsum spoil (i.e. 68% in South Africa; Blignaut and Milton, 2005, or up to 85% in the India; Sharma et al., 2001). Planting may be especially advantageous in quarry spoils, since planting tasks (e.g. site preparation, digging holes, etc.) can help to overcome common problems for plant development on these materials (e.g. crusting or compaction), and introducing nursery-grown plants raised to a size adequate to cope with adverse conditions (e.g. low water availability during the summer) can help to achieve good survival and establishment. Specifically, Escudero et al. (1999, 2000) reported that survival was size-dependent for *H. squamatum* and *L. subulatum* (i.e. larger plants having a better chance of surviving), and it is probably why low survival has been reported for seedlings emerging in nature (i.e. <40% for *H. squamatum*, and 47.3% for *L. subulatum*; Escudero et al., 1999, 2000) or under greenhouse conditions (i.e. <25% both species, Matesanz and Valladares, 2007). In contrast, the three species tested in our study achieved similar survival to our plantings when sown on the same materials (>70%, Ballesteros et al., 2012), pointing out the need of comparing both restoration approaches in depth. However, since plantings in our study have achieved high survival rates in all the bedding materials, the choice for restoration should also take into account the capacity of materials to encourage species growth and production.

In this sense, raw gypsum and gypsum spoil were the most beneficial materials for growth, flowering, fruiting, and seed production

Table 2
Effect of bedding treatment on plant growth (volume) in the three sampling periods (July 2011, April 2012 and June 2012) considering all species, evaluated fitting a Generalized Linear Mixed Model (GLMM). Bedding treatment, as fixed factor and species as random factor. Random effects for each period are expressed in the last row of the table.

Model effects on plant volume												
	July 2011				April 2012				June 2012			
	Estimate	SE	*z* value	Pr(>|*z*|)	Estimate	SE	*z* value	Pr(>|*z*|)	Estimate	SE	*z* value	Pr(>|*z*|)
Intercept	7.66980	0.54798	14.0	<0.0001	8.52329	0.51237	16.6	<0.0001	10.23510	0.29562	34.6	<0.0001
Raw gypsum	−0.45485	0.00280	−162.6	<0.0001	0.32896	0.00149	220.9	<0.0001	0.71973	0.00064	1120.9	<0.0001
Topsoil	−1.00019	0.00334	−299.6	<0.0001	−1.11411	0.00230	−484.2	<0.0001	−1.57803	0.00130	−1212.7	<0.0001
Marls[a]	−1.27678	0.00594	−214.9	<0.0001	−2.20861	0.00462	−478.3	<0.0001	−2.54901	0.00239	−1065.8	<0.0001
Random effects	Variance: 0.90083		SD: 0.94912		Variance 0.78756		SD: 0.88745		Variance: 0.26217		SD: 0.51202	

[a] The marls treatment was not applied to *Ononis tridentata* subsp. *crassifolia*.

Table 3
GLM results and mean values (±SE) of the parameters evaluated to assess the performance of the three species on each bedding material. Parameters: Vol. = Volume (expressed in dm^3), flower, fruit, and seed production per individual, and seeds per fruit. Different letters indicate significant differences ($p < 0.05$) in the Tukey's post hoc test.

Species	Parameters	χ^2	p	Bedding materials							
				Raw gypsum		Gypsum spoil		Topsoil		Marls	
				N	Mean ± se	N	Mean ± se	N	Mean ± se	N	Mean ± se
H. squamatum	Vol. (dm^3)	1246	<0.0001	41	25.76 ± 3.49a	37	14.38 ± 2.25b	27	1.99 ± 0.66d	44	3.24 ± 0.37c
	Flowers	315,445	<0.0001	41	5366.85 ± 827.76a	37	2487.16 ± 422.47b	27	217.82 ± 63.78d	44	378.68 ± 49.24c
	Fruits	187,657	<0.0001	41	3640.66 ± 681.58a	37	2189.11 ± 361.04b	27	198.93 ± 64.17d	44	455.81 ± 65.21c
	Seeds	723,566	<0.0001	41	13,069.96 ± 2446.88a	37	8636.38 ± 1424.35b	27	492.58 ± 158.89d	44	1588.01 ± 227.18c
	Seeds/Fruit	8.6912	0.0337	30	3.59 ± 0.14ab	31	3.95 ± 0.14a	21	2.48 ± 0.19b	31	3.48 ± 0.12ab
L. subulatum	Vol. (dm^3)	6341.1	<0.0001	49	71.33 ± 5.68a	50	40.90 ± 3.00b	48	4.94 ± 0.78c	50	0.86 ± 0.09d
	Flowers	4,129,794	<0.0001	49	42,505.39 ± 4475.53a	50	19,115.30 ± 1955.29b	48	1453.44 ± 329.70c	50	47.42 ± 13.84d
	Fruits	3,594,211	<0.0001	49	37,466.88 ± 4806.23a	50	16,422.94 ± 1888.93b	48	1428.42 ± 292.08c	50	51.32 ± 16.98d
	Seeds	5,940,637	<0.0001	49	61,595.55 ± 7901.44a	50	26,523.05 ± 3050.62b	48	2202.53 ± 450.37c	50	71.28 ± 23.58d
	Seeds/Fruit	0.50554	0.9177	25	1.64 ± 0.05	20	1.62 ± 0.06	31	1.54 ± 0.04	18	1.39 ± 0.11
O. tridentata subsp. *crassifolia*	Vol. (dm^3)	2219.8	<0.0001	27	98.10 ± 13.67a	30	35.11 ± 4.51b	30	13.78 ± 2.36c	–	–
	Flowers	153,001	<0.0001	27	3557.85 ± 547.83a	30	448.94 ± 86.01b	30	88.93 ± 24.25c	–	–
	Fruits	89,981	<0.0001	27	2012.04 ± 313.38a	30	236.58 ± 47.19b	30	36.63 ± 12.68c	–	–
	Seeds	125,130	<0.0001	27	2784.66 ± 433.71a	30	320.80 ± 63.99b	30	49.93 ± 17.28c	–	–
	Seeds/Fruit	0.007517	0.9962	25	1.38 ± 0.05	25	1.36 ± 0.10	12	1.36 ± 0.09	–	–

of all gypsophiles in comparison to topsoil or marls. Significantly larger and more productive plants found on these materials indicated advantageous effects on species development. The greater plant size and production on these materials would likely be due to resource availability (e.g. substrate chemical composition or water availability during the summer). Particularly, these gypsum-rich materials may have reproduced some of the features that gypsophiles find beneficial in their natural habitat. Consistent for most materials in our study, gypsum or sulfur content has been claimed by some authors to increase growth and development of gypsophiles (Meyer, 1986; Ruiz et al., 2003). However, it does not seem conclusive to explain the lower performance in topsoil (Appendix A). Therefore, other factors would have to be modulating plant response. In this regard, water availability during the summer drought has been used to explain active summer growth and summer flowering phenology of most gypsophiles (Escudero et al., 1999, 2000; Meyer, 1986). However, there was more water only in the top 10 cm of raw gypsum and gypsum spoil compared to topsoil during the most active growing and reproductive periods (April to July) (Fig. 2, Appendix B), making it difficult to attribute results only to this factor. In addition, competition has been reported to affect plant performance on this material (Ballesteros et al., 2012), but since aboveground biomass was eliminated in our study, gypsophiles response would rather be modulated by the edaphic properties of the material. Nevertheless, although the reasons for better performance on raw gypsum and gypsum spoil are not conclusive, both materials have proved to greatly benefit gypsophiles, so that their use in restoration would be very positive to recover the three species tested in areas affected by quarrying.

By contrast, topsoil and marls proved to be less beneficial for gypsophiles. Since smaller and less productive plants were recorded on these materials, their use suggests only limited benefits for the introduction of the target species by planting. Restoration guidelines for mining-disturbed areas (e.g. Department of Industry, Tourism and Resources, 2006; Department of Minerals and Energy Western Australia, 1996; Jorba et al., 2010, etc.) and many authors have recommended the use of topsoil to provide a seed bank and to enhance soil properties for improved plant development and revegetation (e.g. Castillejo and Castelló, 2010; Ghose, 2004; Tormo et al., 2007). However, this treatment did not enhance species performance in our study, and its effectiveness at assisting the unaided (neither planting nor sowing) restoration of the whole gypsum community would need to be demonstrated. In this sense, previous studies have reported competition when applying topsoil for gypsum-quarry restoration, hindering the development of gypsophile species (Ballesteros et al., 2012; Castillejo and Castelló, 2010). However, since the competition was eliminated in our study, the poor response of gypsum species would rather be related to topsoil edaphic properties. Similarly, marls proved less appropriate as a potential alternative to enhance the performance of the three study species in a potential scenario where gypsum had been depleted, since this treatment showed the worst growth and production results in general. Thus, the restoration of the disturbed area would be better undertaken by the application of a layer of raw gypsum or gypsum spoil jointly with the planting of gypsum species.

The planting of gypsophiles on raw gypsum and gypsum spoil may benefit not only restoration by reintroducing new individuals into the disturbed area, but may also start seed-bank buildup and increase species opportunities for establishment from their own seed. Accordingly, the choice for restoration should also be based on the capacity of these substrates to ensure the regeneration of the target species, as well as the diversity of the gypsum plant community over the long term. In this regard, despite raw gypsum produced a larger number of seeds in our study, previous sowing tests have shown low recruitment compared to gypsum spoil under the same conditions (Ballesteros et al., 2012). These results suggest that if higher recruitment could be achieved by a smaller but more efficient seed bank, gypsum spoil could constitute an equal or better option to encourage the long-term establishment of these species. Additionally, gypsum spoil has also proved the most beneficial option for the restoration of other desirable scrub species occurring in gypsum habitats in the area (e.g. *Stipa tenacissima, Helianthemum syriacum, Thymus zygis* subsp. *gracilis, Rosmarinus officinalis*) when sown on this material (Ballesteros et al., 2012). Moreover, the use of gypsum spoil in restoration is of particular interest since this material constitutes an inexpensive byproduct of the quarrying operation, produced in large quantities, and used commonly to fill quarry pits before vegetation recovery is attempted, in contrast to the industrial value and the consequent low availability of raw gypsum for restoration. Thus, despite the remarkable success achieved with raw gypsum, the many advantages of gypsum spoil suggest it is the most suitable option to conduct vegetation-restoration works in disturbed gypsum areas affected by quarrying.

Sowing has also proved beneficial for the establishment of gypsophiles in gypsum disturbed environments (Ballesteros et al., 2012; Matesanz and Valladares, 2007), and probably the reintroduction of species such as *H. squamatum* and *L. subulatum* would be more cost effective using this method, since seed harvest at peak fruiting would provide enough seeds for restoration purposes. By contrast, the seeds of the threatened and narrow endemic *Ononis tridentata* subsp. *crassifolia* are often difficult to harvest, highly predated (Ballesteros et al., 2013) and with low germination rates (Cañadas et al., 2014). Thus, propagating this vulnerable species in a nursery would be particularly beneficial for the efficient use of seeds collected for restoration, and given the satisfactory results achieved by planting in our study, this approach could effectively encourage its establishment. Therefore, the choice for restoration method should be based on a sound analysis considering the specific objectives of the project, the availability of seeds and bedding materials, and the cost-effectiveness of each approach (i.e. Gilardelli et al., 2013).

Restoration studies in abandoned quarries (gypsum, limestone, marble, etc.) have demonstrated the strong potential of these areas for biodiversity conservation (e.g. Davis, 1979; Gentili et al., 2010; Mota et al., 2004). Restoration of abandoned gypsum quarries constitute an opportunity for the conservation of specialized and/or endangered species, and should be aimed at creating suitable environments to settle sustainable populations and minimizing the risks of fragmentation of areas of high conservation value in gypsum habitats (Ballesteros et al., 2012, 2013; Dana and Mota, 2006; Mota et al., 2011).

5. Conclusion

In conclusion, the restoration of the gypsophiles *Helianthemum squamatum*, *Lepidium subulatum*, and *Ononis tridentata* subsp. *crassifolia* can successfully be undertaken by planting on bedding materials such as raw gypsum and gypsum spoils. Plantings on these materials achieved good survival as well as enhanced growth and seed production, proving their utility to conduct the restoration. However, gypsum spoil should be recommended, given its low cost, wide availability, and potential for the recovery of the areas affected by gypsum quarrying. Plant-cover regeneration must be evaluated over the long term to guarantee the restoration success and confirm the ecological and economic viability of using these materials over time. By contrast, topsoil and marls were less advantageous for the reintroduction of the study species by planting. Finally, this work highlights the importance of conducting specific research to identify the most beneficial measures for the restoration of conspicuous flora and vegetation in disturbed areas, and specifically those inhabiting gypsum habitats.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecoleng.2014.06.001.

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