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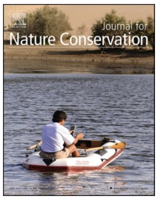

Economic evaluation of ecological restoration options in gypsum habitats after mining

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ABSTRACT

Degraded ecosystems worldwide are in need of restoration in order to recover essential ecosystem services, promoting biodiversity and enhancing carbon stock. Methods to restore vegetation differ widely in economic cost and effectiveness, but economic evaluations are scarce in the literature. The aim was to perform an economic appraisal of different restoration options for gypsum habitats after mining, analysing the effectiveness of the most feasible options comparing both, ecological success (survival) and economic (costs).

The evaluated restoration techniques differed significantly in costs. The most expensive option was planting (69,795.50 €/ha), despite the high survival achieved. The least expensive successful option was manual sowing in level plots (0−15 % incline; 12,513.20 €/ha). The application of organic amendments proved expensive without offering substantial benefits, while the erosion-control blankets (ECBs) justified the cost only on steep slopes (50–60 % incline).

We conclude that for relatively level areas without stability or erosion problems, the simplest and least expensive solution is manual sowing of native species. For steep areas (15−60 %), hydroseeding with dense mulching is the most cost-effective choice, while only small patches with steeper slopes (around 60 %) should be treated with ECBs to prevent excessive erosion and landslides. Restoration requires more ecological research followed by proper economic assessment in order to offer valuable solutions for practitioners, not only in mining restoration, but also in all types of ecological restoration.

1. Introduction

Human exploitation and conversion of ecosystems is causing worldwide biodiversity loss and environmental decline, leading to a reduced provision of ecosystem services (Bullock, Aronson, Newton, Pywell, & Rey-Benayas, 2011; Butchart et al., 2010). Different land-use activities have transformed a large proportion of the planet's land surface, thus posing a dilemma. On the one hand, many land-use practices are essential for humanity, because they provide critical natural resources and ecosystem services, such as food, fibre, shelter, and fresh water. On the other hand, some forms of land use are degrading many habitats and ecosystem services upon which humans depend (Foley et al., 2005).

In this context, degraded ecosystems throughout the world are in need of restoration. Ecological restoration, defined as a "process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (SER, 2002), can potentially help to restore biodiversity and essential ecosystem services. Sometimes natural succession can be key in restoration (Prach et al., 2001). However, ecosystems have frequently been altered to such an extent that they can no longer self-correct or self-renew (Barnosky et al., 2012). Under such conditions, ecosystem homeostasis has been permanently halted and the normal processes of ecological succession (Prach & Walker, 2011) or natural recovery from damage are inhibited in some way, so that intervention to some extent is needed to reach the ultimate goal of restoration (Prach & Hobbs, 2008). This implies creating a self-supporting ecosystem that is resilient to perturbation without needing further assistance (SER, 2004; Urbanska, Webb, & Edwards, 1997), either returning to the original ecosystem or to a desirable alternative state (Suding, Gross, & Houseman, 2004).

Achieving this goal requires sound and scientifically based information from the multidisciplinary science of ecological restoration, providing appropriate best-practice guidelines in policy, planning, and legal efforts (Suding et al., 2015). Ideally, restoration ecologists provide ideas, guidance, and rigorous data that benefit restoration practitioners; in return, practitioners put the science into practice, exchange insights

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with the scientists, and make project sites available for scientists to develop and test their theories (Cabin, Clewell, Ingram, McDonald, & Temperton, 2010).

Techniques and methods to restore the vegetation may differ widely in economic cost, and the efficiency in terms of survival, growth, resilience, and ecosystem services provided (Espelta, Retana, & Habrouk, 2003). Therefore, for practitioners it is crucial to have an economic assessment or at least clues to perform their own appraisal. The economic evaluations of restoration approaches are scarce in the literature and have been focused mostly on evaluating the ecosystem services provided in terms of game, fishing or recreation value (Monz et al., 2013). However, the economic evaluation of ecological restoration techniques themselves are very scarce (e. g. Schuman, Vicklund, & Belden, 2005). Without a proper evaluation of cost and effectiveness of different restoration options, managers often remain sceptical and consider ecological restoration to be economically unviable and even unrealistic. Therefore, we propose two steps in the application of restoration ecology knowledge. First, to compile scientifically based information coming from different restoration experiences, and second, to evaluate the cost and effectiveness of different restoration options, the latter clearly being a pending task.

To explore this issue, we here propose an economic appraisal of different restoration techniques for gypsum habitats, which can be paradigmatic for several reasons. First, gypsum substrates in arid and semi-arid regions are often important habitats for plant conservation that are worthy of being preserved (Moore, Mota, Douglas, Olvera, & Ochoterena, 2014; Pérez-García et al., 2018). In addition, these habitats harbour highly specialized flora with many rare and endemic species that have a range of strategies to cope with the physical and chemical limitations imposed by gypsum substrates (Escudero, Palacio, Maestre, & Luzuriaga, 2015; Meyer, 1986; Parsons, 1976). Furthermore, gypsum is a mineral in global demand (Herrero, Escavy, & Bustillo, 2013), and its extraction by mining inevitably damages valuable gypsum habitats (Chapin, Sala, & Huber-Sannwald, 2001; Mota, Sánchez-Gómez, & Guirado, 2011). Thus, mining companies are usually compelled to conduct restoration programmes despite the lack of information on the most appropriate ecological restoration techniques and procedures. Moreover, the restoration of native vegetation affected by quarrying poses restoration challenges due to the major limitations caused by the alteration of both topography and soil properties (Bradshaw, 2000). Quarrying usually produces low-quality spoil heaps with inherent stability problems, both causing severe difficulties for the reestablishment of the former vegetation (Cohen-Fernández & Naeth, 2013; Espigares, Moreno-De Las Heras, & Nicolau, 2011; Martín-Duque, Sanz, Bodoque, Lucía, & Martín-Moreno, 2010).

Moreover, gypsum imposes specific physical (e.g. low water availability and physical crust formation) and chemical constraints (e.g. S toxicity or Ca and Mg imbalance) (see Escudero et al., 2015 for a review). Also, spontaneous recovery may take considerable time due to site-specific environmental conditions, such as unstable and unsuitable substrates, lack of propagules, or competition with generalist colonizer species (Dana & Mota, 2006; Mota et al., 2004; Prach et al., 2001). These constraints, together with the lack of specific knowledge, result in applying inappropriate restoration measures that fail to rehabilitate the habitat (Ballesteros, 2018), often resulting in wasted effort and money.

In recent years, multiple facets of the ecology of gypsum habitats have been extensively studied (see Escudero et al., 2015; Moore et al., 2014, for a review). Yet, ecological restoration has received comparatively less attention. However, the restoration of gypsicolous flora affected by quarrying has been the focus of some previous studies, based on spontaneous succession (Mota, Sola, Dana, & Jiménez-Sánchez, 2003; Dana & Mota, 2006; Mota et al., 2004), germination and nursery plants (2015, Cañadas, Ballesteros, Valle, & Lorite, 2014; De La Cruz, Romao, Escudero, & Maestre, 2008; Escudero, Carnes, & Pérez-García, 1997; Sánchez, Luzuriaga, Peralta, & Escudero, 2014), sowing (2012, Ballesteros et al., 2017; Ballesteros, 2018), planting (Ballesteros et al., 2014), and the use of restoration techniques such as hydroseeding, erosion-control blankets (ECBs hereafter) (2012, Ballesteros et al., 2017, Matesanz, Valladares, Tena, Costa-tenorio, & Bote, 2006), and organic amendments (2012, Ballesteros et al., 2017; Ballesteros, 2018; Castillejo & Castello, 2010).

Over the last 10 years, we have experimentally tested many of these techniques in order to restore the vegetation of gypsum habitats (see compilation in Ballesteros, 2018). These experiments have moved us to rule out certain restoration actions while identifying the most successful ones. Whereas some of these measures offered reasonably satisfactory results over time (Ballesteros, 2018). We hypothesized that they strongly differed in cost and therefore an analysis of their cost-effectiveness could guide practitioners in restoration choices. As mentioned above, because it is uncommon to have adequate information to perform an economic evaluation of the restoration techniques, our experience through these years provides much-needed guidelines.

In this paper, we aim to analyse the effectiveness of the most successful actions to restore gypsum habitats highly disturbed by mining, and compare them in terms of cost. We offer this study to help managers develop more ecologically and economically effective restoration programmes for disturbed gypsum habitats.

2. Methods

2.1. Experimental area

All the restoration techniques were 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 a.s.l. 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 (data available at Spanish National Meteorological Agency-AEMET). 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 (Aguilar et al., 1992; Aldaya, Vera, & Fontbote, 1980). The predominant soils in the gypsum outcrops are Gypsiric Leptosols (Aguilar et al., 1992). The vegetation of the area is a mosaic of fields with cereal crops, olive (*Olea europaea*) and almond (*Prunus dulcis*) orchards, and scattered patches of native plants growing over gypsum outcrops (Lorite, Cañadas, Ballesteros, Peñas, & Valle, 2011).

2.2. Target habitat characterization

To set the target habitat for restoration (Bullock et al., 2011), we sampled well-preserved gypsum sites previously mapped within the study area (Ballesteros, Foronda, Cañadas, Peñas, & Lorite, 2013; Lorite et al., 2011). We laid out 82 transects, each of 50 m^2 (25 × 2 m), in May 2012 to coincide with the blooming peak of the habitat. We recorded the number of individuals of all the perennial species (i.e. chamaephytes and hemicryptophytes) within the transects. Then, we calculated each species density (D in individuals per ha) and frequency (F, as the percentage of transects where a given species is found). Species were also classified into two categories according to their preferences for gypsum habitats (following Mota et al., 2011): “gypsophytes”, species that occur exclusively on, or with a clear preference for, gypsum, and which are very rarely found outside this substrate; and “gypsovags”, species that appear both in gypsum habitats and in other substrates (i.e. limestone).

2.3. Data compilation

We selected 10 successful restoration techniques previously tested (2014, Ballesteros et al., 2017, 2012); seven for flat or level plots (slope <15 %) three for steep plots (slope 15–60%) (see Table 2), which

Table 1
Cost of the different actions applied in the restoration options evaluated (Table 2).

Actions	Unit	Cost per unit (Euros)	Cost/ha (Euros)
1. Area conditioning 1, for level areas (0−15% slope)	Ha	10,130.00	10,130.00
2. Area conditioning 2, for steep areas (15−60% slope)	Ha	12,156.00	12,156.00
3. Organic amendment (commercial substrate + substrate addition)	10 l/m^2	1.50	15,000.00
4. Seed collection (manual collection of seeds)	2 people/ day	263.52	5,270.40
5. Plant nursery (seed collection included)	Individual plant	0.90	31,500.00
6. Planting	Individual plant	0.55	19,250.00
7. Manual seed sowing	2 people/ day	263.52	790.56
8. Hydroseeding type 1 (conventional)	m^2	0.44	4,400.00
9. Hydroseeding type 2 (dense mulching)	m^2	0.64	6,400.00
10. Erosion control blanket (esparto grass fibre)	80 m^2 roll	120.80	15,100.00
11. Erosion control blanket installation	2 people/ day	263.52	790.56

succeeded in rehabilitating the target habitat in 5–6 years. For further description on restoration methods used, see table S1. All the seeding and hydroseeding options selected give plant densities over the reference target habitat for overall species (more than 3.22 in./m^2), as well as for each target species individually, justifying their inclusion in our evaluation. All the plots were laid out over gypsum spoil (rocky waste left after the gypsum removal; see composition in table S2). The experimental plots were sampled for composition, density, and survival 12−15 months after the restoration. For this, we randomly laid out 15 quadrats of 0.5 × 0.5 m per plot, resulting in 50–75 samples per treatment (i.e. restoration options, numbers 1–10 in Table 2). We counted all individuals per perennial species (i.e. chamaephytes and hemicryptophytes) species in each quadrat. For planting, individuals were tagged and monitored for 17 months to calculate survival. The survival rate for each restoration technique was calculated as the percentage of surviving individuals from the initial plantings, or from the total seeds used (for sowings). Moreover, we registered the cost of all the inputs and the actions for all the restoration techniques assayed (Table 1), to compare the density and survival results with the cost in each case.

2.4. Economic assessment

For the economic assessment, we followed the scheme shown in Fig. 1. In all cases, we started with bare soil (i.e. the parent geological material composed by a mixture of marls and gypsum), where the substrate was added, with the goal of rehabilitating the target habitat. The target habitat was established according to the composition of the well-preserved patches of remnant gypsum vegetation (table S3). For this, we used the 10 restoration options that successfully restored the target habitat. We registered the cost of all the inputs and the actions for all the restoration techniques assayed (Table 1), to compare the density and survival results with the cost in each case. Each option involved a set of activities (Table 2) with specific associated costs (Table 1). In all the cases the cost of filling in the quarry and remodelling were included in the restoration costs.

This implies that each restoration option bore a different cost for the results achieved, in terms of plant density and survival. The cost-effectiveness comparisons of the different restoration options were used to determine the best option while taking into account other advantages and disadvantages such as target species promotion or erosion control.

2.5. Data analysis

Statistical analyses were performed using R version 3.4.3 (R Core Development Team, 2017). To address differences in density, survival rate, seed collection costs, and total restoration costs we performed permutational ANOVAs by means of lmPerm R package (Wheeler & Torchiano, 2016) a flexible and very robust analysis that could cope with heterocedasticity and a wide variety of statistical distributions. Pairwise multiple comparisons were made by applying the post-hoc Tukey test after the permutational ANOVAs, using the R “multcomp” package (Hothorn, Bretz, & Westfall, 2008), in order to estimate differences within the treatments (restoration techniques) of assessed variables (density, survival rate, seed collection costs, and total restoration costs). For graphs included we used ggplot2 package (Wickham, 2009).

Table 2
Restoration options evaluated (rows **1 to 10**) and required actions (columns in the header). Numbers superscripted in actions correspond to the number assigned in Table 1. See table A1 for further details on the restoration actions.

	Actions										
Restoration options*	Area cond. 1^{1}	Area cond. 2 ^{2}	Org. amend.^{3}	Seed collect.^{4}	Plant nurs.^{5}	Planting^{6}	Seed sow. ^{7}	Hydroseed. 1^{8}	Hydroseed. 2^{9}	ECB^{10}	ECB install.^{11}
< 15 % slope											
1. Planting	✓				✓	✓					
2. Sowing	✓			✓			✓				
3. Sowing + Organic amendment	✓		✓	✓			✓				
4. Sowing + EC blanket	✓			✓			✓			✓	✓
5. Hydroseeding 1 (conventional)	✓			✓				✓			
6. Hydroseeding 1 + EC Blanket	✓			✓				✓		✓	✓
7. Hydroseeding 2 (dense mulching)	✓			✓					✓		
15−60 % slope											
8. Hydroseeding 1 (conventional)		✓		✓				✓			
9. Hydroseeding 2 (dense mulching)		✓		✓					✓		
10. Hydroseeding 1 + EC blanket		✓		✓				✓		✓	✓

[*] *Note*: We did not include all the combinations of the actions, only the tested and successful ones. See Methods for further explanations.

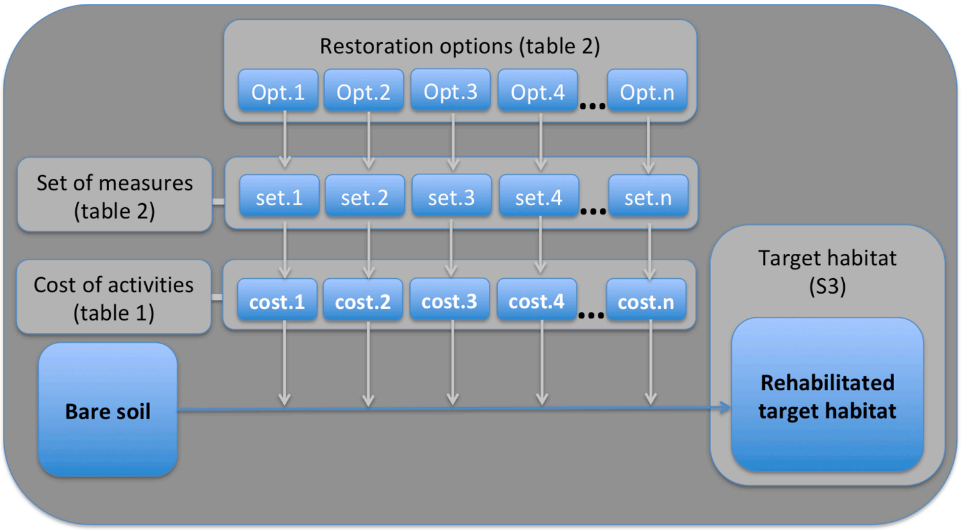

Fig. 1. Conceptual scheme for economic evaluation of the restoration options for the target ecosystem/habitat, starting with the bare soil left after the quarrying activities. Each restoration option (Table 2) comprises a set of actions (Table 2) together with the associated costs (Table 1). Note that all the restoration options proved to rehabilitate the habitat over the period assessed.

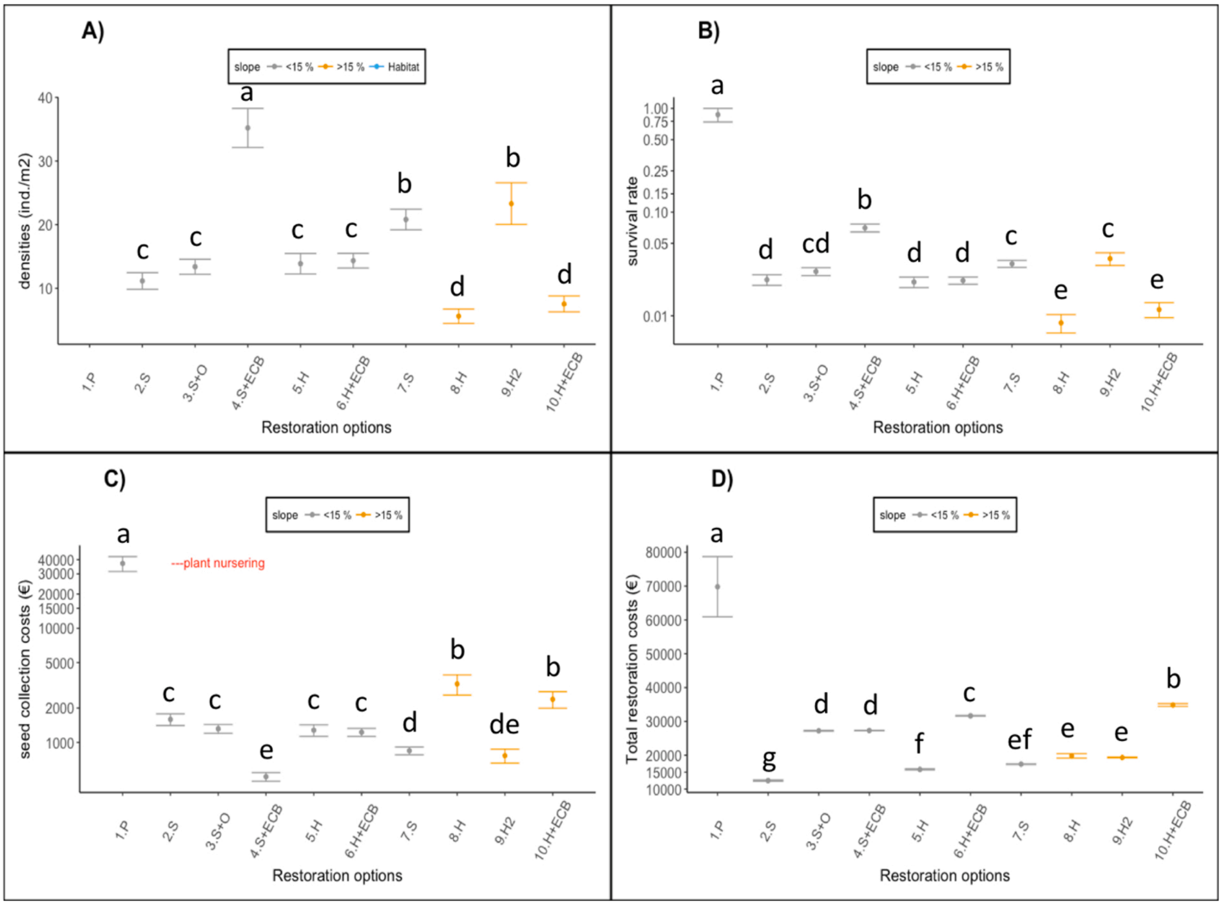

Fig. 2. Results of variables evaluated using 10 different restoration options for habitat recovery: A) Density (individuals per m^2) for the 10 different restoration options for the habitat (mean ± SE). B) Survival rate for planting and sowing (mean ± SE). C) Seed-collection costs (mean, max., min.). Note that, for planting, the amount includes also the cost of collection plus plant nursery. D) Total restoration costs for restoration options (mean, max., min.) See Table 2 and Methods for further details on the restoration options. Different letters over the treatments in a graph indicate significant differences ($p < 0.05$) for the *post hoc* Tukey tests performed after the permutational ANOVAs. Restoration options: Level plots (slope=<15 %) options 1-7: 1.P = Planting; 2.S = Manual Sowing; 3.S + O= Manual Sowing + Organic amendment; 4.S + ECB = Sowing + EC blanket; 5.H= Hydroseeding 1 (conventional); 6.H + ECB= Hydroseeding 1 + EC Blanket; 7.S= Hydroseeding 2 (dense mulching). Steep plots (slope = 15-60 %) options 8-10: 8.H= Hydroseeding 1 (conventional); 9.H2= Hydroseeding 2 (dense mulching); 10.H + ECB= Hydroseeding 1 + EC blanket.

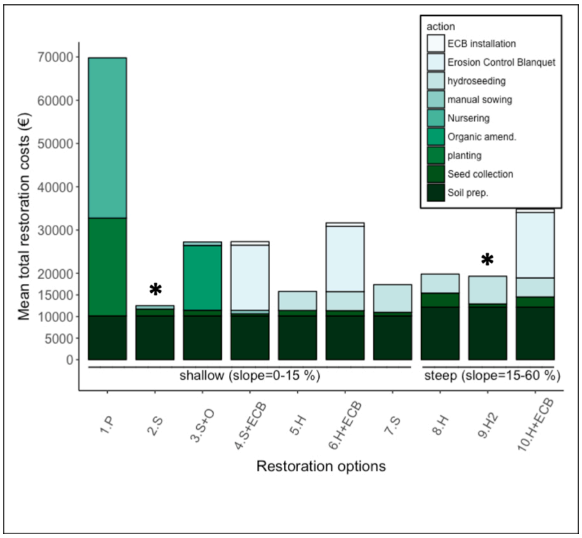

Fig. 3. Mean total restoration costs for each restoration option assessed. Level plots (slope=<15 %) options 1-7 on the left. Steep plots (slope = 15-60 %) options 8-10 on the right. Restoration options: **1.P**= Planting; **2.S**= Manual Sowing; **3.S + O**= Manual Sowing + Organic amendment; **4.S + ECB**= Sowing + EC blanket; **5.H**= Hydroseeding 1 (conventional); **6.H + ECB**= Hydroseeding 1 + EC Blanket; **7.S**= Hydroseeding 2 (dense mulching); **8.H**= Hydroseeding 1 (conventional); **9.H2**= Hydroseeding 2 (dense mulching); **10. H + ECB**= Hydroseeding 1 + EC blanket. * Best restoration options for shallow and steep slopes.

3. Results

Mean plant density of target habitat was 33,200 ± 3600 individuals per ha (table S3), with 1.79 ± 0.17 individuals/m^2 for three gypsophile species and 1.53 ± 0.19 individuals/m^2 for the remaining 10 gypsovags. The most abundant species (more than 100 individuals per ha) were (in this order) *Helianthemum squamatum*, *Thymus zygis* subsp. *gracilis, Ononis tridentata* subsp. *crassifolia*, *Macrochloa tenacissima,* and *Helianthemum syriacum*. All appeared also in more than 80 % of the transects.

The densities calculated in the experimental plots were higher than in the reference target habitat for all the cases (Fig. 2A). For level plots (<15 % slope) densities ranged from 35.2 ± 3.07 indiv./m^2 for manual sowing plus the ECB to 11.14 ± 1.31 indiv./m^2 for manual sowing without any additional treatment. For steep plots (15−60% slope) densities proved lower, ranging from 23.30 ± 3.27 indiv./m^2 for hydroseeding with dense mulching to 5.60 ± 1.13 indiv./m^2 for regular hydroseeding.

The survival rate for planting was high, with the average for all the species exceeding 80 % (Fig. 2B), and reaching up to 98 % for some species of gypsophiles (e.g. *Lepidium subulatum*). The survival rate for sowing was comparatively low, as expected. However, it was quite high for some seeding plots (for example, 7.04 ± 0.61 % for manual sowing plus ECB). The lowest survival rate was found in steep plots using regular hydroseeding. After the survival rates for each option (Fig. 2B), we obtained the average cost for seed collection (Fig. 2C) as well as the range of the cost (max-min) in € per ha for each restoration technique (Fig. 2D).

Total restoration costs (Fig. 2D) differ significantly among the different restoration techniques. The most expensive restoration option by far was planting, despite the high survival rate. For this option, the average estimate cost was 69,795.50 €/ha, and also with major uncertainty (up to 78,711.10 € in the worst scenario). Also, comparisons of the mean costs of each restoration option (Fig. 3) show that restoration by planting (additional costs of nursery included) was by far the most expensive.

Restoration in steep plots required more expenses than in the level plots, due to the higher cost of landscape remodelling and the more complex techniques applied (e.g. ECB and hydroseeding). The average cost of the most expensive sowing option was 3,257.00 €/ha (max 3,914.20- min 2,599.80) for hydroseeding in steep plots. By contrast, the least expensive sowing option was manual sowing plus the organic blanket on level slopes, with an average of just 500.90 €/ha (max 544.60-min 457.20). Remarkably, the same densities by means of planting would cost 37,033.80 €/ha (max 42,567.60 - min 31,500.00), i.e. more than 10-fold higher than with seedings (Fig. 2C).

The application of ECBs or organic amendments were also expensive techniques and failed to offer substantial benefits in terms of plant density or survival compared to the cheaper options assayed (Fig. 3).

The cheapest successful option was manual sowing in level plots with an average expense of 12,513.20 €/ha (max 12,325.90 - min 12,700.90). With a fixed expense of 10,130.00 € just for soil preparation, the cost of the restoration *sensu stricto* was remarkably low (2,383.20€ /ha).

4. Discussion

Successful results for gypsum-habitat restoration involved the use of appropriate techniques and native species (e.g. Ballesteros et al., 2017, 2014, 2012; Cañadas et al., 2015; Dana & Mota, 2006). Here, we test and then economically assess some of these techniques, finding major differences in their cost effectiveness, coinciding with similar approaches in other biomes (e.g. Schuman et al., 2005), or other habitats within the Mediterranean (e.g. Espelta et al., 2003).

First, in all the cases the cost of filling in the quarry and remodelling it were included in the restoration costs obtained. Remarkably, this remodelling represents the highest expenses in most restoration options. These activities are often a preliminary step that the law requires of quarrying firms in most countries, even when habitat recovery is left to spontaneous succession (Bradshaw, 1996; Prach and Hobbs, 2008).

The pros and cons for direct seeding vs. planting of seedlings have been largely controversial. Sowing is usually easy to perform because it requires no infrastructure for plants, no nursery care, and no specific knowledge (i.e. germination requirements). Remarkably, sowed plants can develop a larger root system and establish crucial symbiotic relationship with mycorrhiza and bacteria from the beginning of their life cycle (Smith & Read, 1997). Additionally, it is easier to achieve nature-like distribution patterns in the field by sowing (Ballesteros et al., 2014; Robinson, 2004). Usually the densities that small plants reach in nature can also be easier to reproduce than by planting and it is less costly in economic terms.

However, a sere of disadvantages could arise from sowing. Germination and the first stages of plant development are more exposed to negative effects of environmental factors (e.g. drought, extreme temperatures, low nutrient content, soil chemical imbalance, substrate hardening, seed predation, etc.). This results in lower survival rates for sowing in comparison with planting (Palma & Laurance, 2015). However, this is not a major problem for common species, since high quantities of seeds can be easily collected in the nature. Also, the plant's life cycle (i.e. from seed to adult plant) tends to be slower than when planting for most species. Also, some species do not germinate until the first or second year following sowing (Rieger, Stanley, & Traynor, 2014). Moreover, to obtain similar relative proportions of those of the target habitat is more difficult through sowing, since the final result depends on multiple and sometimes unpredictable factors (seed provenance, seed viability, dormancy, environmental stochasticity, etc.).

In addition, planting also shows advantages and drawbacks. Nurseries, required for planting, control environmental factors such as excessive irradiation, drought, winds, lower temperatures, predation, etc., provide higher survival rates per seed (Palma & Laurance, 2015). This is especially important for rare and/or threatened species, frequent in gypsum habitat, for which the seeds can usually be collected only in small quantities (Ballesteros et al., 2013).

Once in the field, there is a critical acclimatization phase, where

Table 3
Summary of the pros and cons for the restoration techniques evaluated. Data extracted and adapted from: Ballesteros, 2018; Ballesteros et al., 2014, 2012; Ballesteros et al., 2017; Cañadas et al., 2015; Castillejo & Castello, 2010; García-Palacios et al., 2010; Matesanz et al., 2006; Matesanz & Valladares, 2007. Effects on each key process were categorized as follows: **(+++)** optimal, **(++)** fairly positive, **(+)** positive, **(-)** negative, **(–)** fairly negative and, **(—)** very negative effect. Costs were calculated here (see results and Figs. 2,3).

	Density promoting	Survival	Erosion control	Slope stabilizing	Colonizer avoidance	Target species promotion	Costs
< 15 % **slope**							
1. Planting	- - -	+++	- -	- -	++	+++	- - -
2. Sowing	++	+	–	- -	+++	+++	+++
3. Sowing + Organic amendment	++	+	–	–	+	++	- -
4. Sowing + EC blanket	+++	+++	+++	+++	- - -	- -	- -
5. Hydroseeding 1 (conventional)	++	++	++	+	- -	–	- -
6. Hydroseeding 1 + EC Blanket	+++	+++	+++	+++	- - -	- -	- - -
7. Hydroseeding 2 (dense mulching)	+++	++	+++	+	–	+	- -
15–60% slope							
8. Hydroseeding 1 (conventional)	+	+	+	+	+	++	+++
9. Hydroseeding 2 (dense mulching)	++	++	++	++	++	+++	+++
10. Hydroseeding 1 + EC blanket	+++	++	+++	+++	- -	+	- - -

environmental factors are harsher than in the nursery. However, controlled drought stress in the nursery through water limitation can increase drought resistance (Van den Driessche, 1992). This critical establishment period is usually followed by a faster growth period, particularly when two- or three-year-old plants are used (Van den Driessche, 1992).

Also, we stress that planting requires infrastructure, specialized knowledge, and optimal nursery techniques, aside from higher cost of material and labour that planting involves. As we pointed above, in our case, the planting of gypsophiles is by far the most expensive option. Moreover, the development of the seeds from sowing is fast and almost all surviving individuals become reproductive after the first year (Ballesteros et al., 2012). Under these circumstances, even with the high survival rate achieved with planting (average survival above 87 %), the excessive cost makes this option unfeasible in almost all cases. Also, for the restoration of steep areas it becomes impractical because of the difficulty to access and work on such steep slopes. Nevertheless, it can be a feasible option in restoring woodland or habitats composed of long-lived perennial species (Espelta et al., 2003; Palma & Laurance, 2015; Robinson, 2004).

The application of organic amendment promoted higher plant growth, survival and cover (2012, Ballesteros et al., 2017). Based on this faster cover, some authors have suggested that gypsum-quarry rehabilitation can be accelerated by using organic amendments to improve physical (structure) or chemical (nutrient content) soil properties (Castillejo & Castello, 2010). However, the improvement of the soil parameters and the offering of a more suitable germination microsites usually promote the appearance of undesirable colonizer species that slow down the recovery of the target habitat (Ballesteros et al., 2017). Therefore, according to our findings the acquisition and application of amendments add a high and unnecessary cost to the restoration (about 15,000 €/ha).

The use of restoration techniques such as hydroseeding or ECBs have largely proven to be effective (Brofas & Varelides, 2000), also for gypsum habitats (2012, Ballesteros et al., 2017). However, for more level areas this adds unnecessary costs (between 4400 and 15,900 €/ha), that would be only justified for small patches to treat stabilization or erosion problems. In level patches these techniques can also have the negative effect of promoting colonizers and other undesirable plants (2012, Ballesteros et al., 2017). In the steep areas, manual sowing is not feasible because of the erosion and consequently the movement of the seeds that cause a failure in the application of this cheaper technique. Under these circumstances, stabilization techniques must be applied. Organic blankets provide the best protection against erosion, although they promote colonizers (Ballesteros et al., 2017). Hydroseeding with dense mulching provide better results in terms of density and survival. This technique creates germination microsites and reduces seed loss caused by erosion and run-off. For this reason, despite being more expensive than regular hydroseeding, after including the survival rate, the costs are similar but the results (erosion control, stabilization, etc.) are more problem free. Consequently, hydroseeding with dense mulching is the best choice for most situations, except certain areas with severe stability problems, where ECBs could be the most effective choice.

For a selection of the best restoration technique for each scenario, aspects such as erosion control, slope stabilization, colonizer avoidance, and target-species promotion should be balanced with the economic evaluation. Table 3 offers a summary compiling and interpreting the findings from the few other studies available in the literature. We conclude that for more level areas without stability or erosion problems, the simplest and the cheapest method is manual sowing of native species. Regarding steep areas, hydroseeding with dense mulching is the most effective choice. Finally, small areas with steep slopes (around 60 %) must be treated with an ECB to stabilize the slope and to prevent excessive erosion and landslides.

The restoration of heavily impacted areas, such as mining areas is challenging (Bradshaw, 2000; Cooke & Johnson, 2002). However, as we can conclude after our results, different techniques resulting in a successful restoration could greatly differ in terms of economic costs. Consequently, an experimental scientific approach is needed in order to economically assess the ecological restoration techniques, finding the necessary trade-off between ecological and economic issues.

In fact, many practitioners are reluctant to use the results without an economic evaluation, fearing that techniques developed in restoration ecology science are expensive and difficult to apply, whereas the contrary is true in most cases (Bullock et al., 2011). Nevertheless, including a proper economic evaluation can help to assess the best ecological restoration options, as we stated in this assessment on gypsum habitats restoration. Thus, it is necessary to provide this information to practitioners with the proper cost evaluation, as this is difficult to find in the literature. Ideally, restoration projects must be a success not only in ecological terms, but also for stakeholders that seek for the best cost-benefit solution (Palmer et al., 2005).

More scientific research is needed on restoration, but research on this field should be followed by proper economic assessments in order to offer feasible solutions for practitioners from the field of ecological restoration, and not only in mining restoration, but also in all types of active ecological restoration.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jnc.2020.125935.

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