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Long-term effects of topsoil transfer assessed thirty years after rehabilitation of dry alluvial quarries in Southeastern France

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Abstract

Of the many techniques tested to date to rehabilitate degraded ecosystems, topsoil transfer appears to offer the best results. However, this method is recent, and results achieved in the short term (months to years) may not provide a sound indication of long-term vegetation reestablishment. In the plain of La Crau in southeastern France, many dry alluvial quarries were exploited in the 1970s -1980s and are nearly all now abandoned. Various topsoil transfers were performed when operations ceased, for various rehabilitation purposes (aesthetic, security, agricultural, etc.) and now provide the opportunity to test their efficacy in the 30-year long-term. We used an ecological analysis of plant communities and soil carried out in 2015 to compare the reference ecosystem (the steppe of La Crau, positive control) with un-rehabilitated quarry pits (negative control) and with four different rehabilitation treatments: (1) soil transfer (40 cm) with no contact with the water table; (2) soil transfer (40 cm) in contact with the water table; (3) more than 40 cm of soil transfer and (4) anthropogenic material deposits (spoils) unrelated to the characteristics of the reference soil. Our results show that the treatment most favorable to restoration of the species richness, diversity and composition of the steppe vegetation is transferring soil with fine particles (clay, silt) (treatment 1), at least 40 cm thick and without contact with groundwater. However, even after thirty years, and the re-establishment of traditional sheep grazing, full restoration of the reference steppe is far from being achieved. The other treatments lead to the emergence of hybrid or novel ecosystems, such as temporary ponds, riparian woodlands or matorrals with new variables and common variables to the historical ecosystem. Additional techniques to enhance the effectiveness of topsoil transfer are discussed.

Keywords: alpha diversity, gamma diversity, quarry rehabilitation, Mediterranean ecosystem, soil analyses, steppe plant community.

1. Introduction

The constant acceleration of urbanization and industrialization worldwide, with the ensuing demand for mineral resources, means that newly-created quarries have largely destroyed many natural ecosystems (Wang et al., 2011). Quarrying results in significant visual and ecological impacts (Simón-Torres et al., 2014), not all of which have been identified yet (El-Taher et al., 2016). Quarrying causes drastic alterations. It destroys flora and fauna, thereby reducing biodiversity and disrupting fundamental ecological relationships. Moreover, it extensively damages soil by modifying the original site topography and depleting and altering soil microbial communities (Corbett et al., 1996; Pinto et al., 2001; Milgrom, 2008; Mouflis et al., 2008; Simón-Torres et al., 2014). Other impacts identified at regional level include nuisance to local residents, with dust, noise pollution and ground vibrations when topsoil is dug up with heavy machinery (Mohamed and Mohamed, 2013; Dontala et al., 2015). Quarrying can also cause chemical contamination of groundwater by increasingly hazardous materials (Misra, 2013; Dontala et al., 2015).

Today, many countries have legislation requiring mining and quarrying companies to implement ecological restoration after closure (DITR, 2005; UNEP et al., 2005; European Parliament, 2014). Ecological restoration *sensu lato* is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed (SER, Society for Ecological Restoration International, Science & Policy Working Group, 2004). The goals of restoration *sensu stricto* include the re-establishment of the pre-existing biotic integrity in terms of species composition and community structure. Many quarries thus implement rehabilitation or reclamation actions of benefit to biodiversity (Damigos and Kaliampakos, 2003; Carrick and Krüger, 2007). Rehabilitation seeks to repair one or more ecosystem attributes, processes, or services. Reclamation, on the other hand, includes land stabilization, public safety guarantees, aesthetic improvement and usually a return of the ecosystem considered useful in the regional context (Society for Ecological Restoration International, Science & Policy Working Group, 2004).

Numerous experiments conducted worldwide testify to the many quarry rehabilitation techniques in use, in particular for vegetation. For example, shrub species were planted in dolomite rock quarries in China (Wang et al., 2011) or in limestone quarries in Portugal (Oliveira et al., 2011) to rehabilitate areas formerly degraded by an increased bare ground soil surface sensitive to water or wind erosion. This involved adding an improved marl substrate layer on top of the bare rock (Oliveira et al., 2011). Other techniques using substitute substrates with fertilizers, water-holding polymers, geotextiles and mycorrhizal inoculations were used to enhance vegetation growth after marble mining in Spain. However, long-term monitoring is rarely implemented, and those results available are not encouraging (Oliveira et al., 2011). Yet this rather limited effect of rehabilitation contrasts with the sometimes high diversity found in some abandoned quarries (Remacle, 2009; Chapel, 2011; Prach et al., 2013; Pitz et al., 2014). This paradox suggests a need to determine the most beneficial measures for the rehabilitation of singular flora and vegetation in disturbed areas, and for research specifically aimed at those inhabiting quarry habitats (Oliveira et al., 2011; Ballesteros et al., 2014).

One of the most frequently used techniques is to cover the post-quarrying exposed geological substrate, either with a layer of topsoil removed pre-quarrying and conserved in stockpiles during quarrying (topsoil transfer) (Simón-Torres et al., 2014), or with an artificially created soil (artificial soils) (Frouz et al., 2008; Weber et al., 2015). Topsoil transfer consists in removing the uppermost centimeters of topsoil from a donor site of ecological interest. This topsoil can be the pre-existing soil from the site itself, or can come from another site already programmed for destruction (Bulot et al., 2016). The soil is then re-spread on the sites to be restored (Ghose, 2001; Sheoran et al., 2010). It can consist in a direct topsoil transfer from another site that begins to be exploited. In such case, there is no storage of topsoil and therefore a better chance of rehabilitation successful (Rivera et al., 2014). In other cases, topsoil is stored for the duration of mining exploitation, the quality of soil and seed bank are then altered and this reduces the chances of rehabilitation success (Ghose, 2001; Strohmayr, 1999). Topsoil transfer can be used to save ecological features and their associated ecosystem services from donor sites (Box, 2003). It has been evaluated as the best rehabilitation method to compensate for the many projects necessarily involving destruction to make way for consented or permitted development (Box, 2014). However, success monitoring rarely exceeds the first few years (Koch, 2007; Oliveira et al., 2011; Muller et al., 2013; Bulot et al., 2014; Jaunatre et al., 2014a; Bulot et al., 2016). Most restoration involving soil transfer has been recent and/or has not been examined scientifically (Fowler et al., 2015). The long-term effects (over several decades) of topsoil transfer on target species survival are therefore not known. Moreover, results obtained in the first months or years after implementation do not necessarily provide a good indication of longer-term responses (Cooke and Johnson, 2002; D'Antonio and Meyerson, 2002; Herrick et al., 2006; Oliveira et al., 2011; Gaucherand et al., in press). Studies assessing medium- and long-term results are, therefore, essential for a fuller evaluation of these techniques.

In the plain of La Crau in southeastern France, many dry alluvial quarries were exploited in the 1970s for the creation of the Fos-sur-Mer port zone. These activities resulted in the destruction of nearly 300 hectares of the unique La Crau steppe ecosystem (Buisson and Dutoit, 2006). When quarrying ceased fifteen years later, the companies were not required by law to rehabilitate the environment after mining. Various rehabilitation trials, mainly using different soil transfer techniques, were thus implemented, mainly with aesthetic aims (i.e. creating a flat area like the steppe landscape) or security objectives (i.e. to avoid potholes).

Monitoring the soil and vegetation of these quarry pits today therefore provides the opportunity for 30-year long-term feedback on these techniques (i.e. involving different soil sources, composition, thickness and with or without contact with the groundwater table). Plant communities and soil physico-chemical parameters in rehabilitated pits were compared to a positive control, the steppe, generally considered as the reference ecosystem (Dutoit et al., 2013; Hobbs et al., 2013) and to a negative control without any soil transfer treatment. The soil of this surrounding steppe was the one that existed before it was destroyed by quarrying. To evaluate the biological importance of the newly created habitats, we worked at different spatial scales. We took into account both local (alpha) and regional biodiversity (gamma diversity), as well as the originality of the plant communities in relation to a landscape repository.

2. Materials and methods

2.1. Study site

Our study was carried out in the plain of La Crau, located in southeastern Mediterranean France (Bouches-du-Rhône) (Fig. 1A). Characterized by a unique natural habitat, the plain was classified in 1990 as a Special Protection Area under Natura 2000, called *Steppe of La Crau*, the last remaining French Mediterranean steppe (Buisson and Dutoit, 2006). Its Mediterranean substeppic grassland plant community features the phytosociological association *Asphodeletum fistulosii* (Molinier and Tallon, 1950) dominated by species such as *Brachypodium retusum* (Pers.) P. Beauv, *Thymus vulgaris* L. and *Asphodelus ayardii* Jahand and Marie. This plant community is unique in terms of species richness, composition and diversity (Cherel, 1988; Badan et al., 1995; Henry, 2009). There are on average 30 to 40 plant species per square meter, 50% of which are annuals (Römermann et al., 2005). This plant community may result from a regressive or allogenic plant succession of thousands of years under the combined effects of i) the dry and windy Mediterranean climate, ii) specific soil conditions: the 40 cm deep soil is composed of 50% siliceous stones and lies on a calcareous conglomerate which cannot be penetrated by plant roots (Molliex et al., 2013) and iii) a recurring disturbance regime constituted by itinerant sheep grazing since the end of the Neolithic period (Badan et al., 1995; Lebaudy, 2004; Henry et al., 2010; Tatin et al., 2013).

Our study site was located in the south of the plain of La Crau (43°31'36.77''N, 4°53'04.50''E). Present on the site are 296 ha of open quarries once exploited for road ballast or materials for the construction of docks in the Fos-sur-Mer port zone (Fig. 1). All these quarries were abandoned in the 1980s, as seen from old aerial photographs (1938 - 2015) (Fig. 2). A shallow Haplic Cambisol soil WRB (IUSS Working Group WRB, 2006) 40 cm deep lying above the geological conglomerate (composed of quartz pebbles in a calcium carbonate matrix forming a limestone 1 to 5 m thick), hereafter named topsoil, was removed from these quarries and exported, sold or stored. This made way for quarrying the underlying geological substrate (a 10 to 50 m thick mixture of Quaternary pebbles and sands deposited in a former large alluvial fan during the Riss-Wurm glacial period, (Molliex et al., 2013)) below the conglomerate.

In most quarry pits (44% of the study site area), no material was replaced after quarrying, leaving exposed the un-disturbed geological material, or the surface of the water table when quarrying went more than nine meters deep (average water table height). We therefore considered this situation a negative control with no attempt at rehabilitating the soil or the vegetation for ecological or other reasons (Table 1). However, in some cases, quarry pits were partly filled with anthropogenic spoil materials combining various proportions of gravels, clays and sands, conglomerate or concrete blocks, etc. (11% of the study site area). This situation was considered as a rehabilitation treatment, since these new artificial soils provided conditions favorable to new primary plant successions, even though nothing was done to drive these successions towards the plant composition and dynamics of the reference steppe plant community. Contrastingly, at the initiative of certain quarry operators, other quarry pits had stored topsoil re-spread on top of the spoil materials (45 % of the study site area) to various depths, including a depth similar to the reference steppe (40 cm) and a greater depth (more than 40 cm of topsoil added).

Differing quarry operating conditions, followed by differing rehabilitation treatments in the eighties, provided us with a great diversity of artificial geomorphological and pedological situations whose impacts on the present vegetation could be compared. We compared this vegetation both to the steppe vegetation (positive control) generally considered as the reference ecosystem in the previous restoration projects realized in this area (Dutoit et al., 2013), and to quarry pits with no rehabilitation treatments (negative control) (Table 1). In total, four situations were identified along a rehabilitation gradient: (1) soil transfer (40 cm) with no contact with the water table, (2) soil transfer (40 cm) in contact with the water table, (3) more than 40 cm of soil transfer and (4) anthropogenic deposits (spoils) (Table 1). These four situations were identified by the use of ancient aerial photographs (Fig. 2), soil profiles and interviews of quarry operators.

Fig. 1. Location of study site and experimental design. (A) Location of the plain of La Crau area in France and location of the remnant patches of steppe (striped grey) and quarries (black); (B) experimental design of the different rehabilitation treatments realized on the abandoned quarries in the 1980s: 40 cm soil transfer (dark grey); > 40 cm soil transfer (black); anthropogenic deposits (white) and no rehabilitation (light grey).

Fig. 2. Quarry expansion in the seventies and eighties visible from old aerial photographs (1968 – 1974 – 1984 – 2011 -IGN). The extension of intensive orchard areas since 1984 can also be observed between the quarries.

Table 1. Various rehabilitation treatments and controls used in this study and analyses performed on each treatment

	Treatments	Sample number for soil analyses	Transect number for vegetation sampling
Positive control	Reference Steppe	5	6
Topsoil transfer	40 cm soil transfer with no contact with the water table	4	4
	40 cm soil transfer in contact with the water table	5	3
	> 40 cm soil transfer	5	3
Anthropogenic soil	Anthropogenic deposits (spoils)	5	5
Negative control	No rehabilitation: absence of deposits or soil spreading in the quarried geological substratum	5	4

2.2. Vegetation analyses

Vegetation sampling using 4 m² quadrats was carried out in May 2015. For each of the six treatments, depending on available area, 3 to 6 100-meter transects were replicated, each composed of five pseudo-replicated quadrats (Fig. 1; Table 1). Quadrats were pseudo-replicated on the same site along each transect, so as to reveal any heterogeneity in the spatial distribution of plant communities for the same treatment. The number of replicated transects differed according to type of treatment in the quarries sampled. On each transect, quadrats were spaced more than 10 m apart, to prevent spatial autocorrelation between quadrats (Buisson et al., 2006). The abundance of each plant species was visually estimated, in percent cover (Gillet, 2000).

2.3. Soil analyses

Soil analyses were carried out on twenty-nine 200g soil samples taken from abandoned quarries in 2015 (Table 1). Samples were extracted from the first ten centimeters of the upper soil/material layer in February 2015. Each sample was dried and sieved with a 2 mm mesh sieve. Chemical content (organic C (Allison, 1965), total N (Bremner, 1996), C:N, CEC Metson (Metson, 1956; Ciesielski et al., 1997), K, P₂O₅ (Olsen, 1954), CaCO₃, pH (Sparks et al., 1996; Thomas, 1996)) and fine particle sizes (<2 mm) (percentages of clay: <0.002 mm; fine silt: 0.002–0.02 mm; coarse silt: 0.2–2 mm; fine sand: 0.05–0.2 mm; and coarse sand: 0.2–2 mm) (Gee and Bauder, 1986) were measured without decarbonization by the soil analysis laboratory at INRA (*Institut National de la Recherche Agronomique*) in Arras.

2.4. Data analysis

To test the effects of treatments on physico-chemical parameters, soil characteristics were ordinated using principal component analysis (PCA) (6 treatments $\times$ 29 soil samples), a method appropriate for continuous variables (Borcard et al., 2011).

To test the effects of the different treatments on species richness, plant community composition and structure, these variables were compared between treatments. Community structure was measured using different indices (alpha diversity, gamma diversity, CSII_{norm} and HAI index). Alpha diversity, which is the number of species present in a plant community, was calculated for each 4 m² quadrat. Gamma diversity, which is the total number of species in a landscape, was calculated as the cumulated species-richness of the five quadrats for each transect in the different quarries and the reference steppe. As the number of transects used in the quarries (N = 19) is higher than in the steppe (N = 6), six quarry transects were randomly selected and their cumulated species-richness was calculated. This operation was repeated 100 times. Mean cumulated species richness determined quarry gamma diversity. Two indices were used to assess the success of plant community rehabilitation by topsoil transfer: the CSII_{norm} index (normalized Community Structure Integrity Index) measuring the proportion of the abundance of the species of the reference community represented in the community of the restored community, and the HAI index (Higher Abundance Index) measuring the proportion of the abundance of species in the restored community which is higher than in the reference community (Jaunatre et al., 2013). When parametric conditions were met, we used ANOVA tests followed by post-hoc Tukey HSD tests if a significant difference was detected. When parametric conditions were not met, we used non-parametric Kruskal-Wallis tests followed by pairwise Wilcoxon comparisons with a *p-value* adjustment according to Bonferroni if a significant difference was detected (Bonferroni, 1936).

Vegetation composition and abundance were ordinated using non-metric multidimensional scaling (NMDS) (6 treatments $\times$ 125 quadrats $\times$ 241 plant species) based on Bray-Curtis dissimilarity (Borcard et al., 2011). We were thus able to visualize the vegetation structure of each treatment and to compare them.

All the analyses were conducted using R 2.13.0 (R Development Core Team, 2011), multivariate analyses with the “ade4” (Chessel et al., 2004; Dray and Dufour, 2007; Dray et al., 2007) and “vegan” (Oksanen et al., 2015) packages.

3. Results

3.1. Effect of topsoil transfer on soil physico-chemical parameters

The different rehabilitation treatments showed significant differences in soil physico-chemical properties (Table 2, Fig. 3). The PCA ordination based on soil properties significantly discriminated the different treatments. Axis 1 (45.3% of inertia) separated topsoil (steppe and soil) transfer from the negative control with no spoil deposits or soil spreading. This separation is explained partly by the quantities of clay, which were significantly higher in the steppe and soil transfers. Conversely, in the absence of deposits or soil spreading, the substrate was characterized by significantly higher amounts of coarse sand, higher C:N ratios and higher pH.

Axis 2 (25.8% of inertia) clearly separated the soils of the reference steppe and of the soil transfer treatments from those of the negative control and spoil deposits. The soils

of topsoil transfer treatments tended to be closer to that of the reference steppe, especially those which were not in contact with the water table.

Table 2

Soil analyses for each rehabilitation treatment realized in May 2015. The given values are means $\pm$ standard errors. The F value and p value are from ANOVA and the X² value is from Kruskal-Wallis tests on the effects of treatments on each variable. Two values in the same row with a different letter are significantly different according to Tukey post-hoc tests or Mann–Whitney–Wilcoxon tests (Bonferroni, 1936).

	Statistic parameter	p-value	Reference steppe (Positive control)	Topsoil transfer (40 cm) with no contact with the water table	Topsoil transfer (40 cm) in contact with the water table	Topsoil transfer (More than 40 cm)	Anthropogenic material deposits	No rehabilitation Absence of soil spreading/material deposits (Negative control)
Clay (g kg ⁻¹)	X ² =19.38, Df=6	0.004**	231.2 $\pm$ 6.6 b	199.5 $\pm$ 33.9 b	223.4 $\pm$ 4 b	204 $\pm$ 17.5 b	109.8 $\pm$ 28.1 a	98.8 $\pm$ 8.9 a
Fine silt (g kg ⁻¹)	F _{6,27} = 1.7	0.16	210.8 $\pm$ 5.5	173.5 $\pm$ 15.3	177.4 $\pm$ 2.7	176.8 $\pm$ 6.5	150.8 $\pm$ 46.3	131.6 $\pm$ 13
Coarse silt (g kg ⁻¹)	F _{6,27} = 0.56	0.76	143.0 $\pm$ 3.7	116.5 $\pm$ 11.6	128.4 $\pm$ 2.6	123.6 $\pm$ 5.9	123.8 $\pm$ 66.1	81.2 $\pm$ 6.9
Fine sand (g kg ⁻¹)	F _{6,27} = 0.5	0.801	202.8 $\pm$ 5.1	239.5 $\pm$ 34.9	218.0 $\pm$ 6.2	205.8 $\pm$ 5.3	224.0 $\pm$ 47.1	234.6 $\pm$ 16.1
Coarse sand (g kg ⁻¹)	F _{6,27} = 2.91	0.026*	212.2 $\pm$ 13.6 a	271.0 $\pm$ 26.9 ab	252.8 $\pm$ 3.4 ab	289.8 $\pm$ 29.1 ab	391.6 $\pm$ 118.7 ab	453.8 $\pm$ 35.5 b
Total carbon (g kg ⁻¹)	F _{6,27} = 1.1	0.385	17.4 $\pm$ 1.4	12.4 $\pm$ 2.1	15.4 $\pm$ 1.9	15.9 $\pm$ 1.6	31.7 $\pm$ 15.6	11.4 $\pm$ 3.2
Total nitrogen (g kg ⁻¹)	F _{6,27} = 0.72	0.637	1.6 $\pm$ 0.1	1.1 $\pm$ 0.2	1.4 $\pm$ 0.1	1.5 $\pm$ 0.2	2.2 $\pm$ 1.3	0.8 $\pm$ 0.3
C:N	F _{6,27} = 2.72	0.034*	10.7 $\pm$ 0.3 a	11.8 $\pm$ 1.8 ab	10.7 $\pm$ 0.5 ab	10.9 $\pm$ 0.6 ab	22.1 $\pm$ 6.2 b	15.1 $\pm$ 0.9 ab
pH	F _{6,27} = 4.31	0.004**	7.6 $\pm$ 0.3 a	8.2 $\pm$ 0.2 ab	8.3 $\pm$ 0.1 ab	8.2 $\pm$ 0.1 ab	8.7 $\pm$ 0.2 b	8.6 $\pm$ 0.1 b
CaCO ₃ (g kg ⁻¹)	X ² = 19.38, Df=6	0.004***	5.8 $\pm$ 4.8 a	70.8 $\pm$ 62.3 a	20.8 $\pm$ 5.7 a	58 $\pm$ 46.1 a	216.6 $\pm$ 20.4 b	223.4 $\pm$ 19.1 b
P ₂ O ₅ (g kg ⁻¹)	X ² = 10.59, Df=6	0.102	0.184 $\pm$ 0.173	0.009 $\pm$ 0.001	0.014 $\pm$ 0.003	0.030 $\pm$ 0.0162	0.016 $\pm$ 0.010	0.026 $\pm$ 0.008
CEC Metson (cmol + kg ⁻¹)	F _{6,27} = 1.37	0.261	9.1 $\pm$ 0.4	7.1 $\pm$ 1.3	8.4 $\pm$ 0.2	7.8 $\pm$ 0.4	8.7 $\pm$ 4	3.4 $\pm$ 0.6
Ca (g kg ⁻¹)	F _{6,27} = 2.89	0.026*	2.8 $\pm$ 1 a	4.1 $\pm$ 1.1 ab	4.9 $\pm$ 0.6 ab	4.3 $\pm$ 1 ab	6.7 $\pm$ 0.4 b	6.4 $\pm$ 0.1 b
K (g kg ⁻¹)	F _{6,27} = 1.32	0.282	0.1 $\pm$ 0	0.1 $\pm$ 0	0.2 $\pm$ 0	0.1 $\pm$ 0	0.1 $\pm$ 0.1	0.1 $\pm$ 0

Fig. 3. PCA ordination based on 29 soil sample analyses. Samples from each rehabilitation treatment and control are identified by dashed lines: (1) soil transfer (40 cm) with no contact with the water table in white (2) soil transfer (40 cm) in contact with the water table in light grey (3) more than 40 cm of soil transfer in medium grey and (4) anthropogenic material deposits in dark grey. Both samples from controls are identified by solid lines: Steppe in white, No rehabilitation in grey. Arrows represent soil variables (chemical content (organic C, total N, C:N, CEC Metson, K, P₂O₅, CaCO₃, pH) and fine particle sizes (<2 mm) (percentages of clay (<0.002 mm), fine silt (0.002–0.02 mm), coarse silt (0.2–2 mm), fine sand (0.05–0.2 mm) and coarse sand (0.2–2 mm))

3.2. Effect of topsoil transfer on plant communities

3.2.1. Alpha and gamma diversity

Vegetation inventories allowed us to identify 21 plant taxa of conservation interest out of the 241 species recorded in total (nearly 10%): 5 with high conservation priority and 16 with moderate conservation priority on the red list of the Provence-Alpes-Côte-d’Azur region (Table 3). 224 species were inventoried in the quarries, including 20 regional red list species and 131 in the reference steppe, including 11 regional red list species (Table 3). Only one plant species of conservation interest was identified in the steppe: *Phlomis lychnitis* L., against 11 in quarries. Four species were recorded in anthropogenic material deposits alone (*Bupleurum semicompositum* L., *Limonium cuspidatum* (Delort) Erben, *Limonium echioides* (L.) Mill., *Velezia rigida* L.) and one in the negative control (*Lythrum hyssopifolia* L.) (Table 3). All plant species of conservation interest identified in the topsoil transfer areas were also identified in the reference steppe vegetation, except for *Campanula erinus* L. and *Paronychia capitata* (L.) Lam. (Table 3).

Table 3

Species of conservation interest identified for each treatment in May 2015. The species' regional conservation status was determined from the regional red list of the Provence-Alpes-Côte-d'Azur region (Noble et al., 2015)

Species	Regional conservation status	Reference steppe (Positive control)	Topsoil transfer (40 cm) with no contact with the water table	Topsoil transfer (40 cm) in contact with the water table	Topsoil transfer (More than 40 cm)	Anthropogenic material deposits	No rehabilitation Absence of soil spreading /material deposits (Negative control)
<i>Bupleurum semicompositum</i> L.	Moderate					x	
<i>Campanula erinus</i> L.	Moderate		x	x		x	x
<i>Centaurea melitensis</i> L.	Moderate	x		x		x	
<i>Gastrium ventricosum</i> (Gouan) Schinz & Thell.	Moderate	x		x	x		
<i>Limonium cuspidatum</i> (Delort) Erben	Strong					x	
<i>Limonium echinoides</i> (L.) Mill.	Moderate					x	
<i>Linaria arvensis</i> (L.) Desf.	Moderate	x	x	x		x	
<i>Lythrum hyssopifolia</i> L.	Moderate						x
<i>Melilotus indicus</i> (L.) All.	Moderate					x	
<i>Parapholis incurva</i> (L.) C.E.Hubb.	Moderate	x		x	x	x	x
<i>Paronychia capitata</i> (L.) Lam.	Moderate		x			x	
<i>Phlomis lychnitis</i> L.	Moderate	x					
<i>Polygala monspeliaca</i> L.	Moderate	x			x		x
<i>Polypogon maritimus</i> Willd.	Moderate					x	x
<i>Psilurus incurvus</i> (Gouan) Schinz & Thell.	Moderate	x	x	x	x	x	x
<i>Ruta Montana</i> (L.) L.	Moderate	x	x				
<i>Taeniatherum caput-medusae</i> (L.) Nevski	Strong	x	x	x	x	x	x
<i>Trifolium glomeratum</i> L.	Strong	x	x	x		x	
<i>Trifolium subterraneum</i> L.	Moderate	x			x		
<i>Valerianella microcarpa</i> Loisel.	Strong				x	x	
<i>Velezia rigida</i> L.	Strong					x	

At the regional scale (gamma diversity), the mean species richness of the plant communities of the different rehabilitation treatments (156.78 ± 0.77) was higher than the mean species richness of the reference steppe vegetation (130 ± 0) ($F_{1, 198} = 1219$, $p < 0.001$). However at the scale of the plant community, the species richness (alpha diversity) of the different topsoil transfer treatments (contact with water table (47.6 ± 2.02); no contact with water table (36 ± 1.20); more than 40 cm soil transfer (35.55 ± 1.46)) showed no significant difference from the vegetation of the reference steppe (42.2 ± 1.51) (Fig. 4). In contrast, the average species-richness on anthropogenic material deposits (29.88 ± 2.66 species) and on the negative control (23.25 ± 1.64) was significantly lower than in the steppe ($F_{5, 119} = 18.98$, $p < 0.001$) (Fig. 4).

Fig. 4. Means and standard errors of species richness (4m²) for each treatment and the two controls: steppe (white), topsoil transfer (light grey), anthropogenic material deposits and absence of soil spreading (dark grey). Within a treatment, bars sharing common letters are not significantly different according to Tukey post-hoc test.

3.2.2. Effects of topsoil transfer on plant community composition

The NMDS ordination showed a gradient in plant community composition, from the steppe (positive control) to the no-rehabilitation negative control, and clearly discriminated plant communities (NMDS-Stress= 0.20) (Fig. 5).

In the NMDS axis1-axis2 plane, the reference steppe was characterized by its most representative species, such as perennial species (*Eryngium campestre* L., *Stipa capillata* L., *Phlomis lychnitis* L., etc.), especially *Brachypodium retusum* (Pers.) P. Beauv., usually dominant in the steppe plant community. It was also characterized by annual species such as *Aegilops ovata* L., *Clypeola jonthlaspi* L., *Cynosurus echinatus* L., *Hedypnois cretica* Willd., *Reseda phyteuma* L., *Stipa capillata* L., *Trifolium arvense* L., which were recorded only in the steppe.

The reference steppe community was close to the two topsoil transfer treatments with no contact with the water table ("> 40 cm topsoil transfer" and "40 cm topsoil transfer with no contact with the water table") (Fig. 5). These two plant communities overlapped and were characterized mainly by grasses and thistles, such as *Avena barbata* Brot., and *Galactites tomentosus* Moench., as well as *Euphorbia cyparissias* L., *Marrubium vulgare* L., *Medicago truncatula* Gaertn., etc.. This was confirmed by the CSII_{norm}, which showed that only 18 to 22% of species identified in topsoil transfer plant communities were also

present in the steppe community with the same composition, abundance and richness (Fig. 6A) even thirty years after these rehabilitation treatments were applied.

The topsoil transfer in contact with the water table showed a different plant community composition from that of the reference steppe. It contained *Anagallis arvensis* L., *Catapodium rigidum* (L.) C.E.Hubbs., *Hypericum perforatum* L., *Stellaria media* (L.) Vill., *Veronica arvensis* L., etc. (Fig. 5), pioneer species common to anthropogenic and wetland margin environments.

In the NMDS axis1-axis2 plane, the rehabilitated areas (the topsoil transfer and the anthropogenic material deposits treatments) and the reference steppe were also clearly separated from the no-rehabilitation ("negative control") treatment in terms of plant community composition (Fig. 5). The no-rehabilitation control was characterized by pioneer annual target species also occurring in the reference steppe, such as *Centranthus calcitrapae* (L.) Dufr., *Valerianella locusta* (L.) Laterr., *Velezia rigida* L., and other non-target species such as *Artemisia annua* L., *Pyracantha coccinea* M. Roem. (Fig. 5). These last two species can be considered potential invasive species. Due to the presence of the water table, this area contained temporary wetland species such as *Lythrum hyssopifolia* L., a species of conservation interest.

The plant communities identified in quarries were far from similar to those of the reference steppe ($F_{5, 119} = 227.20$, $p < 0.001$) (Fig. 6A) in terms of composition, richness and diversity. Not only did they not include all reference steppe species, but they included other species not present in the steppe community (*Anagallis foemina* Mill., *Anagallis arvensis* L., *Cynodon dactylon* (L.) Pers., *Dittrichia viscosa* (L.) Greuter, *Medicago orbicularis* (L.) Bartal., *Rumex pulcher* L., etc.). The $CSII_{norm}$ index showed a significant difference between treatments (Fig. 6A). The anthropogenic material deposits treatment and the no-rehabilitation treatment showed a significantly lower $CSII_{norm}$ index than the reference steppe (Fig. 6A). The HAI index was relatively high both in the different rehabilitated areas and in the no-rehabilitation treatment, and significantly different from that of the reference steppe ($F_{5, 119} = 88.66$, $p < 0.001$) (Fig. 6B).

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400 **Fig. 5.** NMDS ordination based on 125 vegetation samples (4m²) and 175 species present in at least 3
401 samples. For clarity, only the 63 most correlated species are shown. Samples from each rehabilitation
402 treatment are identified: (1) soil transfer (40 cm) with no contact with the water table in light green (2) soil
403 transfer (40 cm) in contact with the water table in blue (3) more than 40 cm of soil transfer in dark green
404 and (4) anthropogenic material deposits in red. Both samples from control are identified: steppe in yellow,
405 absence of material or soil spreading in grey.
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407
408 **Fig. 6.** Means and standard errors of normalized Community Structure Integrity Index (A) and higher
409 Abundance Index (B) for each treatment: steppe (white), topsoil transfer (light grey), anthropogenic
410 material deposits and absence of soil spreading (dark grey). Within a treatment, bars sharing common letters
411 are not significantly different according to Tukey post-hoc test.
412

4. Discussion

Topsoil transfer has been recognized as the best method for restoring soil and vegetation when this resource has been conserved or is available elsewhere (Box 2014, Bulot et al., 2014, in press). To date, however, the restoration success of this technique has mainly been assessed over the short term (a few years after treatment). Assessing restoration over the long term (several decades), our results show that topsoil transfer is still the best method, especially when initial soil characteristics (thickness, absence of contact with the water table) are respected. Nevertheless, in our case, soil transfer still does not compensate for the destruction of the pre-existing ecosystem: the steppe soil and plant community have not yet fully recovered even thirty years after its application. These results confirm those of Holl and Cairns, Mulligan et al., Nichols (Holl and Cairns, 1994; Mulligan et al., 2006; Nichols, 2006), who found that plant community composition was never completely restored after rehabilitation, in quarries or elsewhere. However, it is generally acknowledged that natural successions towards steppe occur on quarries after topsoil applications and re-vegetation is positive, although species composition still differs from that of the reference steppe (Martínez-Ruiz and Fernández-Santos, 2005).

The negative control, where there was no rehabilitation, no transfer of materials or soil, is the worst situation compared to the undisturbed reference steppe in terms of total number of plant species and total number of plant species of conservation interest. In 30 years, only a fraction of the steppe vegetation has recovered. This is due to the depth of quarrying, which involves potential contact with the water table. New primary plant succession is therefore blocked by irregular changes in ground water table levels, including by the extreme conditions that develop between dry and flood periods (Prach et al., 2014; Balázs A. Lukács et al., 2015; Deák et al., 2015; Masson et al., 2015). The lack of rehabilitation, together with the new abiotic conditions created by quarrying, thus generated “novel ecosystems” (Hobbs et al., 2009). The long-term dynamics of these new ecosystems are unknown, since we have no experience of similar habitat conditions, and because they are also impacted by global change (climate and land-uses) (Doley and Audet, 2013; Hobbs et al., 2013). However, we do know that these environments will not spontaneously evolve towards the reference steppe in the long-term, barring any major ecological change (significant and permanent reduction in the level of the water table). Usually, for these radically disturbed mining sites, it is not practicable to aim for the restoration of historical ecosystems. However, hybrid or novel ecosystems, which consist of new combinations of physical and biological components with new variables and variables common to historical ecosystems, could provide acceptable levels of stability and functionality (Doley and Audet, 2013). For example, vegetation may include both native species and non-native species.

Deposition of various types of anthropogenic materials after the end of quarrying created great heterogeneity in terms of physico-chemical soil parameters, but less diversity and species-richness in terms of vegetation. However, these materials provide some very specific habitats for certain species of high conservation value, which have particular ecological requirements linked to their narrow ecological niche. At some places on our site, depositing sandy salty soils excavated closer to the Mediterranean coast has provided a habitat for *Limonium cuspidatum* (Delort) Erben and *Limonium echioides* (L.) Mill., two halophytic species of conservation interest at the regional scale. However, deposition of anthropogenic materials is certainly not the best method to restore plant

communities similar to the reference steppe in the plain of La Crau. A better method might be steppe geomorphological rehabilitation by filling the bottom of quarry pits, thus isolating the upper transferred soil layers from the water table (Meredith, 2007; Frouz et al., 2008; Mchergui et al., 2014). Nevertheless, our results show that spoils must be covered by at least 40 cm of topsoil from the reference steppe.

Thus, topsoil transfer appears to be the most favorable treatment for rehabilitation of the reference sub-steppe plant community, in terms of physico-chemical properties and plant community composition. Our long-term results on soil transfer restoration confirm those obtained over the short term by Bulot et al. (2014) and Jaunatre et al. (Jaunatre et al., 2014a, 2014b) for the same steppe area. Our study shows that these reconstituted soils present the most favorable abiotic conditions for restoring the reference steppe, particularly because they entail no significant differences in fine particle size content from the soil of the reference steppe (Buisson et al., 2006; Bulot et al., 2016; Römermann et al., 2005). However, the plant communities identified in these treatments cannot yet be considered similar to those of the reference steppe vegetation, as measured by the various diversity indices. Soil alone does not account for the diversity of vegetation encountered here after different types of soil transfer. Other factors are involved, such as the plant composition of the different surrounding patches, i.e. steppe, abandoned quarries, fallow land, orchards, etc. (Pärtel et al., 1998; Zobel et al., 1998), the reproduction capacity of their communities, the presence of dispersal vectors (Bakker et al., 1996; Ozinga et al., 2004) and between-species competition or facilitation (Maestre et al., 2009; Teixeira et al., 2016). The topsoils transferred most probably had a very poor seed bank, having been conserved in large piles for several years, and the soil of the reference steppe is known to have a very poor permanent seed bank (Römermann et al., 2005; Buisson et al., 2006; Saatkamp et al., 2009; Rivera et al., 2012; Bordez, 2015). Therefore there would be very little similarity between the topsoil transferred and the reference steppe seed banks. Soil transfers in contact with the water table are ruled out as a restoration treatment aiming to restore the vegetation from the reference steppe (Mediterranean xeric grasslands), since they favor species adapted to moist soils, such as *Scirpus holoschoenus* subsp. *romanus* (L.) auct., *Aster squamatus* (Sperng.) Hieron, etc.. The solution would be to reconstitute the conglomerate bedrock occurring in the reference steppe, or to deposit spoil materials covered by topsoil as described above, which would prevent plant roots from reaching the water table.

Compared to techniques that only impact species dispersion, such as hay transfer (Hölzel and Otte, 2003; Coiffait-Gombault et al., 2011a, 2011b; Török et al., 2012) or seeding (Oliveira et al., 2014; Gilardelli et al., 2016), topsoil transfer offers the best results, both by dispersing target species and by at least partially recreating soil abiotic conditions (Box, 2003; Jaunatre et al., 2014b). However, real success is only possible if certain criteria are met. The topsoil's particle size fraction needs to be adequate and it should not contain blocks of conglomerate that will raise soil CaCO₃ content. This could negatively impact some slightly acidophilus species which characterize the steppe vegetation, especially "tonsures" (vegetation patches composed of very small vegetation, dominated by bryophytes, lichens and vascular plants that are more acidophilus and xerophilous than other steppe species (Coiffait-Gombault, 2011)).

Confirming findings by Simón-Torrez et al. (Simón-Torres et al., 2014), our study demonstrates that in the long term, the best way to restore the reference steppe vegetation is by using the most similar soil, which has conserved its fine particle size fraction, with a thickness

of at least 30 to 40 cm and without contact with the water table (Redente et al., 1997; Holmes, 2001; Bowen et al., 2005). Schladweiler et al. (Schladweiler et al., 2005) found that 30 cm of topsoil produced the greatest diversity; while they found that more than 50 cm ensured the greatest biomass, this was not our goal here. Despite topsoil transfer, 30 years was not sufficient to reach the reference state, even though the traditional sheep-grazing regime was re-established after quarry abandonment. Other factors may have been involved in changing the plant succession. At soil level, fine elements such as clays could have been lost by leaching during soil transport and / or the storage phase (Weng et al., 2004; Zeng et al., 2011). This would have modified soil physico-chemical properties and consequently the plant communities that developed there (Citeau, 2008; Amir et al., 2014). On our soil transfer treatments, species richness was similar to the steppe, but the most dominant species of the steppe was still absent (*Brachypodium retusum*). Conversely, species not present in the steppe were able to develop. In all cases, our monitoring should be pursued on the long-term. There is clearly room for improvement in the methods used for future restoration of quarries still in operation. Topsoil transfer in turfs could be one answer (Good et al., 1999; Vécrin and Muller, 2003; Bulot et al., 2014), as this method allows the conservation of the soil structure (Bulot et al., 2014). The transfer could also be direct, without storage, thereby limiting degradation of the soil and of the seed bank (Granstrom, 1987; Jones and Esler, 2004; Fenner and Thompson, 2005; Hall et al., 2010; Golos and Dixon, 2014). This would also ensure that plant species remain established on the turfs, preventing undesired species implantation. Although direct topsoil transfer is advocated, it is often not feasible because soil in place in the steppe may not be available when required for transfer (Bulot et al., 2014). When only ordinary soil transfer is possible, storage time must be as short as possible: numerous studies have shown the negative impact of soil storage (Strohmayer, 1999; Stahl et al., 2002; Boyer et al., 2011; Park et al., 2011; Golos and Dixon, 2014; Bordez, 2015). Storage can lead to negative impacts on the soil seed bank. Direct topsoil transfer results in loss of less than 50% of the soil seed bank, whereas stockpiling causes loss of 80-90% (Koch et al., 1996). In addition, stored soil piles form a barrier and can trap many non-target anemochorous species (Bordez, 2015). Storage can also cause rotting of organic matter when piles are too high (Stahl et al., 2002). It is therefore recommended that soil be stored on low elevation piles (Bordez, 2015). Moreover, while soil transfer may go some way toward restoring the reference ecosystem, the trajectories of rehabilitated ecosystems are not those of the reference steppe ecosystem. Additional techniques should be implemented to enhance restoration, such as seeding target species or removing undesirable species (Bordez, 2015). For example, native species seeding favors the development of native species to the detriment of exotic or ruderal species (Norman et al., 2006).

In conclusion, topsoil transfer methods can be enhanced by various techniques offering prospects of improved restoration. This should encourage current quarrying operations to implement these findings when planning for rehabilitation.

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