Ecological Engineering 99 (2017) 1–12

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

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

Julie Chenot[a,b,*], Renaud Jaunatre[c], Elise Buisson[a], Thierry Dutoit[a]

[a] Institut Méditerranéen de Biodiversité et d'Ecologie (IMBE), Université d'Avignon et des Pays de Vaucluse, UMR CNRS IRD Aix Marseille Université, IUT site Agroparc, BP 61207, 84911 Avignon cedex 09, France
[b] Société des Carrières de La Ménudelle, 13. BP 80011, 13551 Saint-Martin-de-Crau, France
[c] Université Grenoble Alpes, Irstea, UR EMGR, 2 rue de la Papeterie-BP 76, F-38402 St-Martin-d'Hères, France

ARTICLE INFO

Article history:
Received 28 April 2016
Received in revised form
19 September 2016
Accepted 13 November 2016
Available online 17 November 2016

Keywords:
Alpha diversity
Gamma diversity
Quarry rehabilitation
Mediterranean ecosystem
Soil analyses
Steppe plant community

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.

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 &

---

* Corresponding author at: Institut Méditerranéen de Biodiversité et d'Ecologie (IMBE), Université d'Avignon et des Pays de Vaucluse, UMR CNRS IRD Aix Marseille Université, IUT site Agroparc, BP 61207, 84911 Avignon cedex 09, France.

E-mail addresses: chenot.julie@gmail.com (J. Chenot), renaud.jaunatre@irstea.fr (R. Jaunatre), elise.buisson@univ-avignon.fr (E. Buisson), thierry.dutoit@univ-avignon.fr (T. Dutoit).

http://dx.doi.org/10.1016/j.ecoleng.2016.11.010
0925-8574/© 2016 Elsevier B.V. All rights reserved.

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 (SER, 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, geo-textiles 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; Strohmayer, 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, 2016; Jaunatre et al., 2014a). 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 ha 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.