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Impact of quarry exploitation and disuse on pedogenesis

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ABSTRACT

Quarrying represents one of the oldest and most important human activities; the impacts of which have largely influenced vegetation and landscape. Despite its character as a vital and non-renewable resource, the soil has been poorly studied with regard to either the impact resulting from the exploitation of quarries or its restoration after exploitation. In the plain of La Crau (south-eastern France), numerous dry alluvial quarries were exploited in the 1970s. Their exploitation lasted about ten years and they were then rapidly abandoned. At that time, there was no legal obligation to restore sites after their abandonment. In this context, following various modes of exploitation (e.g. exploitation depth), various rehabilitation options were implemented: no rehabilitation, topsoil transfer, deposits of anthropogenic materials. The absence of legislation consequently resulted in heterogeneous areas after their abandonment. Today, we have the benefit of 35 years of hindsight on the dynamics of these ecosystems resulting from these exploitation modes and rehabilitation options and thus various questions arise: (1) Did the diversity of the modes of exploitation result in heterogeneous soils 30 years after abandonment? (2) At what stage of pedogenesis are the soils created in the abandoned quarries? (3) Did the various rehabilitation options have an impact on the traces of biological activity in the soils of the quarries? (4) Is it possible to identify methods of rehabilitation of quarries that would favour the rehabilitation of the soils and the recolonisation of the plant cover in order to improve the techniques in use or to propose alternative methods? The study of soil profiles (with a special focus on biological activity of animals and plants) and soil physico-chemical analyses (pH, $CaCO_3$, C, N, C:N ratio, CEC, exchangeable K^+, plant available P and fine soil particle contents) made it possible to study these questions. Our results confirm that all the soils resulting from the former exploitation modes and rehabilitation options of the quarries present their own specific characteristics (upper soil layer fertility, soil profile vertical organization) which remain very different, even after 30 years, from the characteristics of the destroyed reference soil ecosystem. Pedogenetic processes are very slow or even blocked by the recurrent action of certain environmental parameters. In terms of ecological rehabilitation, only topsoil transfers undertaken under good conditions (same soil thickness as the reference steppe and no contact with the phreatic zone) have allowed to restore most of the physical and chemical properties recorded close to the reference ecosystem soil.

1. Introduction

In the early 21st century, between one third and half of the earth's surface has been transformed by human actions (Vitousek et al., 2008), 85% of it in Europe (Primack et al., 2012). These transformations, still on the increase, are mainly driven by economic and demographic imperatives, associated with the intensive exploitation of the basic resources required for human needs (agriculture, industry, fisheries, international trade, etc.) (Balmford et al., 2002). Among these changes in use, mining represents one of the oldest and most important human activities (Larson et al., 2006). Today, the large number of disused quarries or those in the process of closing down in many countries represent a challenge for the restoration of these severely degraded habitats (Bradshaw, 1997; Darwish et al., 2011; Mouflis et al., 2008). In Europe, > 2.7 billion tons of aggregates are produced each year in 25,000 quarries spread throughout Europe (*Union Européenne des Producteurs de Granulats*, 2015). In contrast to underground mines, the impact of which may be more localised (Bradshaw, 1997), the exploitation of opencast quarries has a direct impact on the environment, and in particular on the vegetation and the soil, since it leads inevitably

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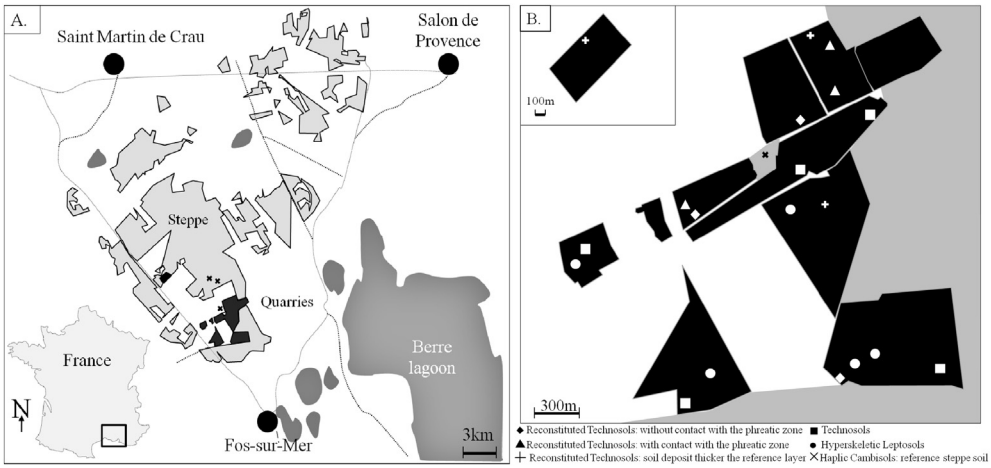

Fig. 1. Location of the study site and soil profiles (A) Location of the plain of La Crau area in France (60,000 ha) and location of the remnant patches of steppe (grey) (10,000 ha) and the former quarries studied (black) (296 ha); (B) location of soil profiles of the different rehabilitation treatments.

to a profound alteration of the composition and/or structure of the soil, or even its complete disappearance. The processes involved in the evolution of highly anthropized soils have yet to be specifically addressed within the soil scientist community. The nature of pedogenetic processes in these soils may be very similar to those in natural soils. However, the presence of purely anthropogenic materials on soil pedogenetic evolution and the nature of pedogenetic processes remain to be explored (Huot et al., 2014).

The studies carried out on the environmental impact of quarries have mainly focused on the vegetation, without taking into account the edaphic conditions (De Deyn et al., 2003). The restoration of these sites after exploitation has thus been mainly focused on the ecosystem compartment that is most often used as the main environmental criterion for assessing the success of the restoration (Koch, 2007). Despite its character as a vital and non-renewable resource (Van-Camp et al., 2004), the soil has been very little studied with regard to either the impact resulting from the exploitation of quarries or its restoration after exploitation. To determine whether we should intervene after exploitation ceased and re-establish the functioning of the ecological communities in the long term, it is necessary to take into account all the compartments of the ecosystem (Bradshaw and Hüttl, 2001) and in particular the soil (Heneghan et al., 2008). Studies should not be restricted to one type of exploitation for a given surface area, but should integrate the diversity of the types of exploitation and post-exploitation redevelopment that are often encountered within the same quarry over time or in a series of quarries situated on the same geopedological unit (Dana and Mota, 2006; Duque et al., 1998; Yuan et al., 2006).

The plain of La Crau (south-eastern France), described as a Mediterranean pseudo-steppe, presents a range of soil, flora, fauna and ecosystem characteristics that confer on it a heritage character (Tatin et al., 2013). Much of this plain is classified as a natural reserve and the protection of its habitats and of the associated species has been in force since 2001 (Beltrando, 2015). Prior to the introduction of this protection, numerous dry alluvial quarries were exploited there in the 1970s to build an industrial port. They resulted in the destruction of part of the original ecosystem (Buisson and Dutoit, 2006). Their exploitation lasted about ten years and they were then rapidly abandoned. At that time, there was no legal obligation to restore the site after ceasing use. In this context, various rehabilitation options were established. Techniques for soil transfer were thus implemented (Bulot et al., 2014), mainly for the purposes of landscaping and safety. In contrast, in other areas, no rehabilitation operation was undertaken, leaving the environment completely bare immediately after exploitation (Chenot et al., 2017). This absence of legislation consequently resulted in a pattern of heterogeneity of these areas after the end of exploitation. Today, we have the benefit of 35 years of hindsight on the dynamics of these ecosystems resulting from the cessation of exploitation of the quarries.

Given these specificities regarding the exploitation, various questions arise: (1) Did the diversity of the modes of exploitation result in a pattern of heterogeneity of the soils 30 years after ceasing use? (2) At what stage of pedogenesis are the soils created in the abandoned quarries? (3) Did the various rehabilitations have an impact on the traces of biological activity in the soils of the quarries? (4) Is it possible to identify methods of rehabilitation of quarries that would favour the rehabilitation of the soils and recolonisation of the plant cover in order to improve the techniques in use or to propose alternative methods? To answer the questions, the various soils taken from a series of abandoned dry alluvial quarries over about thirty years in south-eastern France were described by means of soil profile pits and measurement of physical and chemical parameters. They were then compared with the soils (Cambisol types) that existed before the exploitation of the quarries and which still exist in the vicinity in the landscape matrix constituted of a Mediterranean sub-steppe grassland (Bouteyre and Duclos, 1994). Finally, the coarse fragment cover, plant cover and traces of biological activity observed in the soil profiles (presence of earthworm galleries and roots) characterising the various soils were also compared.

Our hypotheses were as follows: (1) the diversity in the modes of exploitation resulted in a high heterogeneity of the soils encountered in former quarries; (2) the majority of the soils created were rejuvenated artificial soils and/or young intra-zonal type soils bearing little resemblance to the reference steppe soil, except in cases where re-spreading of the original soil was undertaken after exploitation ceased; (3) these alterations have important implications with regard to biological activity traces in soil profiles pits and the cover of the plants spontaneously colonising the soil surface of these former quarries, even in the long term (several decades).

2. Material and methods

2.1. The study site

Our study site is located in the south of the plain of La Crau (43°31′36.77″N, 4°53′04.50″E), south-eastern France (Bouches-du-Rhône) (Fig. 1.A). The plain is characterised by a unique natural habitat classified in 1990 as a Natura 2000 Special Protection Zone, including areas of Mediterranean sub-steppe grassland and disused sites (agricultural, industrial or military). Originally covering > 60,000 ha, the agricultural activities (irrigated meadows, intensive fruit farms, market gardens, etc.), industrial activities (logistical platforms, quarries, etc.) and military activities (ammunition dumps, military airport, etc.) destroyed > 80% of it, and today, only 10,500 ha of non-degraded steppe-type vegetation persists (Tatin et al., 2013).