Impact of quarry exploitation and disuse on pedogenesis

Julie Chenot^{1,2}, Renaud Jaunatre³, Elise Buisson², Fabrice Bureau⁴, Thierry Dutoit²

1. Société des Carrières de La Ménudelle, 13. BP 80011, 13551 Saint-Martin-de-Crau, France

chenot.julie@gmail.com

2. 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

chenot.julie@gmail.com

3. Université Grenoble Alpes, Irstea, UR EMGR, 2 rue de la Papeterie-BP 76, F-38402 St-Martin-d'Hères, France

4. Normandie Univ, UNIROUEN, IRSTEA, ECODIV, 76000 Rouen, France

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, CaCO₃, 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.

Key-words: ecological rehabilitation, Haplic Cambisol, Hyperskeletal Leptosols, soil profiles, Technosols

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, more than 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 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 Hüttel, 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 more than 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 more than 80% of it, and today, only 10 500 ha of non-degraded steppe-type vegetation persists (Tatin et al., 2013).

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.

2.1.1. *The climate of the La Crau plain*

The La Crau plain presents all the characteristics of a Mediterranean climate, with hot, dry summers, relatively mild winters and high solar irradiation. Rainfall is rare but abundant, and is mainly concentrated in the autumn, with more than 50% of the annual total (541 mm/year) (Tatin et al., 2013). The climate is also characterised by the “*Mistral*”, a very frequent, strong cold wind. Its occurrence entails exceptionally high annual rates of solar irradiance (3000 hours/year), enhancing evapotranspiration and thus the summer drought. In winter, it also contributes to lower the temperature.

2.1.2. *The soil of the La Crau plain*

The geographical area of the La Crau plain corresponds to the former fossilised bed of the Durance, generated by deposits washed down during the Quaternary Period (Molliex et al., 2013). The La Crau plain has been formed by alluvial deposits, siliceous pebble and gravel type with sandy matrix between - 2 million years and - 30 000 years, the date of the capture of the Durance by the Rhône to the north of the plain, which then dried up. The thickness of the alluvial deposits ranges between 5 and 35 metres, depending on the location. The soil of the La Crau plain has been identified as Mediterranean red soil (Commission de Pédologie et de Cartographie des Sols, 1967), also referred to as Haplic Cambisol (Calcaric) according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2015). Developed on the ancient stony alluvium of the Durance, these clay-loam soils present between 40 and 80 cm depth a conglomerate or a calcareous crust. This crust results from the dissolution of calcareous stones and the leaching of calcium which is then precipitated in depth (Duclos, 1994). The thickness of this crust may vary between 1 and 5 m, and there may be several layers within the thickness of the alluvium.

Such soils are frequently encountered in stable geomorphological situations that have enabled their development over long periods of time (several hundreds of millions of years) (Tatin et al., 2013). The solum of the La Crau plain is said to be 'truncated' as the topsoil normally rich in fine elements of the silt type is greatly reduced, or even non-existent, a phenomenon resulting from wind erosion concomitant with the deposition. This phenomenon dates from around 10 000 years ago, and exposed the siliceous stones which may then cover more than 50% of the soil surface (Devaux et al., 1983).

2.1.3. *The vegetation of the La Crau plain*

Under the combined effect of climate, multi-secular sheep grazing and specific soil conditions, a particular plant community has developed, resulting in a regressive or allogenic plant succession of thousands of years. It is a plant community described as a sub-steppic grassland of the Mediterranean and belonging to the association *Asphodeletum fistulosii* (Molinier and Tallon, 1950), dominated by *Brachypodium retusum* (Pers.) P. Beauv, *Thymus vulgaris* L. and *Asphodelus ayardii* Jahand and Marie. This plant community is interesting in terms of species richness, composition and diversity (Badan et al., 1995; Cherel, 1988; Henry, 2009). There are on average 40 to 50 species of plants per four square meters, among which 50% are annuals (Römermann et al., 2005).

2.1.4. *The quarries in the La Crau plain*

Our study site has the particular feature of presenting 296 ha of dry alluvial quarries (exploitations of sand, gravel and pebbles) which were mined during the 1970s for the construction of the industrial

port zone of Fos-sur-Mer (Fig. 1) (Devaux et al., 1983). This activity resulted in the destruction of around 300 ha of an original steppe ecosystem (Buisson and Dutoit, 2006). All these quarries were abandoned during the 1980s (Chenot et al., 2017). However, at that time, there was no legal obligation to restore the site after the cessation of mining (DITR, 2005; European Parliament, 2014; UNEP et al., 2005). Consequently, various modes of redevelopment were adopted, ranging from simple abandonment (exploited substrate left bare), to the replacement of the topsoil removed and stockpiled during the period of exploitation, of local backfill (unsold stocks of stones, sand, silt and clay resulting from the decantation processes, etc.) or from imported spoil (inert rubble from deconstruction, etc.), with all the possible combinations. Another source of heterogeneity also derives from the depth of mining. If this is currently limited to 5 m depth to protect the phreatic zone, depths of more than 9 m were reached thirty years ago, exposing the water table in certain quarries.

2.2. Description and analyses of soil profiles

In order to identify the various types of soil present in the quarries and in the steppe, a description of the solum has been undertaken to analyse soil development and disturbances that have occurred. For this purpose pedological pits were described in March 2015 after excavation with a mechanical digger (Fig. 1.B). The pits are situated in the areas that the digger has not been driven over in order to avoid the potential compacting of the soil by the passage of this heavy equipment (Baize and Jabiol, 2011). In all, 20 pedological pits measuring around 1m² with a depth of 0.5 to 1.5 m were dug in homogeneous zones defined on the basis of aerial photographs, the vegetation and the knowledge of the quarry workers regarding former modes of exploitation. The excavation was halted once the subsoil (Durancian pebbles) or the level of the phreatic zone was reached.

Four potential situations were thus identified prior to digging the pits (Table 1): (1) reference steppe soil; (2) reconstituted soils subdivided into 3 categories i.e. (2.1) reconstituted soils with thickness identical to the reference soil (40 cm) without contact with the phreatic zone, or (2.2) with contact with the phreatic zone; (2.3) soil deposit thicker than the reference soil layer (>40 cm); (3) soil with deposits of anthropogenic materials, and finally (4) raw bedrock left on the surface. A minimum of 3 soil profiles were replicated for each type of soil in the quarries and in the reference steppe (Table 1). The soil profiles were described according to the standard procedures using the STIPA 2000 data sheets of the *Institut National de la Recherche Agronomique* (Falipou and Legros, 2002) recommended by the *Association Française d'Etudes des Sols* (Baize and Jabiol, 2011). Then, the denomination of the soil profile and the pedological layers was first done according to the *Référentiel pédologique* 2008 (Baize and Girard, 2008) and then according to the *World Reference Base for Soil Resources* (IUSS Working Group WRB, 2015).

The physical and chemical analyses of the soil were carried out on twenty-nine 200 g soil samples collected in the disused quarries in March 2015. To do this, samples were extracted in the first ten centimetres of the upper soil / material layer. The sample collection was replicated at least four times for each type of soil previously identified on the basis of the soil profiles (Table 1).

Each sample was dried and sieved with a 2 mm mesh sieve. The physical-chemical analyses (pH water ratio 1:5 (Thomas, 1996), CaCO₃ using a Bernard calcimeter (Sparks et al., 1996), organic C (Allison, 1965) and total N by dry combustion (Bremner, 1996; Dumas, 1831), C:N ratio, Cation Exchange Capacity (CEC) and exchangeable K⁺ by Metson (Metson, 1956; Ciesielski et al., 1997), plant available P (Olsen, 1954) and the particle-size distribution in 5 fractions by the Robinson method without prior decarbonisation (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)) were performed by the soil analysis laboratory at INRA (*Institut National de la Recherche Agronomique*), Arras.

Table 1: The different types of soil described in this study and sampling for the various analyses.

Type of soil according to WRB (2015)	Type of soil according to the <i>Référentiel pédologique</i> (2008)	Site specifications	Number of samples for the soil analyses (0-10cm)	Number of soil profiles described	Number of vegetation transects
Haplic Cambisol (Calcaric)	Fersialsols	1. Steppe	5	3	6
Reconstituted Technosols	Reconstituted Anthrosols	2. 40 cm of original soil transfer without contact with the phreatic zone	4	3	4
		3. 40 cm of original soil transfer with contact with the phreatic zone	5	3	3
		4. > 40 cm of transfer of original soil	5	3	3
Technosols	Artificial Anthrosols	5. Deposits of anthropogenic materials	5	5	5
Hyperskeletal Leptosols	Peyrosols	6. Raw bedrock at the surface	5	5	4

2.3. Measurement of traces of biological activity

During the observation of the soil profiles, the traces of biological activity were quantified. They are good indicators of soil function restoration over the whole profile via exchanges between the different soil layers (presence of earthworm galleries and roots). The biological activities and in particular the soil fauna is indeed an integral part of the soil and is indispensable for its development (De Deyn et al., 2003; Frouz et al., 2007). It is used as an indicator of the quality of the environment, and in order to determine the actual functioning of the soil, it is necessary to take it into account in soil studies. Characterised as ecosystem engineers, the earthworms strongly influence the edaphic compartment of ecosystems (Lavelle et al., 1997). The quality of the soil is related to the density and the activity of the earthworms, which improve it (Boyer and Wratten, 2010; De Deyn et al., 2003; Frouz et al., 2007; Pérès et al., 2011). The vegetation is related to these activities since the earthworms aerate the soil and enable better root development, and thus enhanced growth of the vegetation (Whalley and Dexter, 1994). The roots and the earthworms thus play a key role with regard to the generation of the structure of the soil and consequently for the quality of the soil (Whalley and Dexter, 1994).

The traces of the biological activity of animals (earthworms) and plants (roots) have been estimated visually on the whole series of profiles described on the basis of the estimation grids proposed by Baize and Jabiou (Baize and Jabiou, 2011). Various parameters have been taken into account and integrated in the statistical analyses (Appendix A.).

2.4. Percentages of vegetation and coarse fragments cover

The percent cover of the vegetation and of the coarse fragments was visually estimated using 4m² quadrats in May 2015 at the time of peak productivity (Bourrelly et al., 1983). For each type of soil and in function of their surface area, 3 to 6 x 100 meters transects were replicated, each composed of 5

pseudo-replicated quadrats (Table 1). In each transect, the quadrats were placed more than 10 meters apart in order to avoid any spatial auto-correlation between the quadrats.

2.5. Data analysis

All the data analyses were performed using the statistical software R 2.13.0 (R Development Core Team, 2016) and the packages ade4 (Chessel et al., 2004; Dray and Dufour, 2007; Dray et al., 2007), FactoMineR (Husson et al., 2016), JLutils coupled with Devtools (Hadley and Winston, 2016) vegan (Oksanen et al., 2015), and RColorBrewer (Neuwirth, 2014).

2.5.1. Analyses of physical and chemical parameters of the soil

To characterise the physical and chemical parameters of the various types of soil, a Non-metric Multi-Dimensional Scaling (NMDS) was performed on the variables (6 types of soil $\times$ 29 soil samples). On this NMDS were displayed simultaneously the two physical-chemical elements that best contributed to explain the ordination in the different types of soil studied. Analyses and illustrations were made using the package vegan (Oksanen et al., 2015).

Furthermore, univariate analyses were performed on each physical and chemical parameter measured in the soils. When the parametric conditions were encountered, we carried out an ANOVA test followed by a Tukey HSD post-hoc test when significant differences were encountered. When the parametric conditions were not met, we used a Kruskal-Wallis non-parametric test followed by post-hoc tests of Wilcoxon with Bonferroni adjustment if a significant difference was detected (Bonferroni, 1936).

2.5.2. Analyses of indices of the presence of biological activity in the soils

To describe the mode of assembly of the methods adopted for the study of the presence of biological indicators of activity of earthworms and roots, Multiple Component Analyses (MCA) were performed using the packages ade4 (Chessel et al., 2004; Dray and Dufour, 2007; Dray et al., 2007) and FactoMineR (Husson et al., 2016). Several observations may be identical in the MCA when they correspond to the same combination of modalities. Thus these observations are projected on the same point in the factorial plan. They cannot however be observed by means of a classic representation of the results. For that, the packages JLutils, coupled with Devtools (Hadley and Winston, 2016) were used to represent each point of the MCA by a square proportional to the number of observations.

2.5.3. Analyses between types of soil, plant cover and coarse fragments cover

To test possible correlations between the characteristics of the various types of soil, the plant cover and the coarse fragments cover ($> 2\text{mm}$) at the surface, a Kruskal-Wallis non-parametric test was performed. This was followed by pairwise Wilcoxon tests with Bonferroni adjustment to detect significant differences (Bonferroni, 1936).

3. Results

3.1. Analyses of soil profiles

The construction of soil profiles at the bottom of the quarries provided the means to sample several types of soil that were highly differentiated and far removed from the reference steppe soil. According to the techniques of quarrying and redevelopment, the soils of the quarries underwent greater or lesser degrees of degradation with regard to their composition and structure and also highly diverse artificial recomposition.

The exploitation of the quarries involved the destruction of the fersialitic layer (Fs) characteristic of the steppe soil, but also the conglomerate petro-calcareous layer (DxKca) and finally a variable thickness of raw bedrock material composed of alluvium from quarried Durancian pebble. This resulted in Hyperskeletal Leptosols type soils characterised by a single pebble layer (X) more than 10 cm thick. It contains more than 60% of coarse fragments, such as pebbles embedded in a sandy matrix type (Fig. 2). Depending on the depth of the quarrying, this soil layer underwent variations in the height of the water table and may in some cases be flooded for periods of a few days to several weeks. A first stage of pedogenesis (on 1 or 2 cm of topsoil) can then be observed in certain cases, enabling the constitution of a 'young' layer in the topsoil (Js) containing small quantities of organic matter (derived in particular from leaves of *Populus* sp. and *Salix* sp.), though without any bio-macrostructuration.

On this raw bedrock, various anthropogenic materials (earth, asphalt, technological) were deposited and identified in the various pits, either on a single layer, or on several layers deposited directly on the anthropic raw material. From this superimposition result soils referred to as Technosols since they come at 100% from anthropic materials corresponding to "artifacts" in WRB (Fig. 2). These soils may then be constituted from debris (waste materials from the demolition of houses, roads, etc.) or from a hard artificial layer (such as asphalt, concrete, stone, brick, etc., at depth).

The last type of soil encountered results from the re-spreading of the topsoil removed prior to mining. This soil has been replaced directly on the unexploited geological material (Durancian pebble), whatever the level of the phreatic zone, or on other anthropic materials. This results in reconstituted Technosols of which the transferred layer derives from fersialitic layers (topsoil removed and stockpiled prior to mining). From these reconstituted Technosols, 3 modes may be observed at the sites: i) transfer of soil to a thickness of about 40 cm (similar to the thickness of the original fersialitic layer) without contact with the phreatic zone situated at 9 m depth; ii) transfer of soil to a thickness of about 40 cm with fluctuations of the water table in sectors where the mining was in the vicinity of 9 m depth, and iii) transfer of the soil to a thickness of more than 40 cm (generally more than a metre of the fersialitic layer), corresponding to old mounds of soil stockpiled and simply re-spread after mining ceased (Fig. 2).

Fig. 2: Pictures and schemes of soil profiles of reference soil and the different types of soil derived from mining according to the various modes of rehabilitation after cessation of exploitation. The schemas follow the denomination of the *Référentiel pédologique 2008* (Baize and Girard, 2008) for layers denominations and WRB (2015) for soil denomination, (+) siliceous non altered bedrock; (=) Calcium carbonate; Clay 2/1 ; Ferric iron accumulation dehydrated.

3.2. Soils physical and chemical analyses

The soils identified during the description of the soil profiles present clear differences in their physical and chemical properties (Fig. 3). The NMDS based on the properties of soils indeed discriminates between the various soils. Axis 1 separates the Haplic Cambisol (steppe) and reconstituted Technosols (soil transfer) from the Hyperskeletal Leptosols. This distinction is explained in part by the quantity of clay, which is significantly greater in the Haplic Cambisol, and a less alkaline pH. In contrast, in the Hyperskeletal Leptosols, the substrate is characterised by a significantly smaller proportion of clay, but a higher proportion of coarse sand and a significantly more alkaline pH and a larger C:N ratio (Fig. 4). Axis 2 clearly separates the Haplic Cambisol from the Technosols and Hyperskeletal Leptosols. At the surface, the transferred soils tend to be closer to the reference steppe soil, in particular those that are not in contact with the phreatic zone (Fig. 3). Significant differences remain, however, in the fine silt and coarse silt content between these two types of soil (Fig. 4). The dispersion of the points corresponding to the Technosols in the NMDS is also much greater than that of the other soils, reflecting a high degree of heterogeneity of the physical and chemical characteristics of this series of soils according to the type of deposition (Fig. 3). With regard to the coarse fragments (> 2mm) present in the topsoils, the Hyperskeletal Leptosols have almost twice the cover of stones and rocks in comparison with all the other types of soil (Kruskal-Wallis: chi-squared = 38.72, df = 5, p-value <0.05***) (Fig. 4).

Soils also differ in their physic-chemical properties. Technosols and hyperskeletal Leptosols contain significantly higher concentrations of CaCO_3 (Kruskal-Wallis: chi-squared = 19.88, df = 5, p-value <0.01**), Ca ($F_{5,23} = 5.20$, p-value <0.01**) and higher C:N (Kruskal-Wallis: chi-squared = 17.98, df = 5, p-value <0.01**) than other soils (Fig.4). There is no significant difference for the organic matter content (Kruskal-Wallis: chi-squared = 3.89, df = 5, p-value = 0.5654), but Technosols tend to have a higher amount of organic matter than other soils (Figure 4). There were also no significant differences for total nitrogen (Kruskal-Wallis: chi-squared = 6.05, df = 5, p-value = 0.30), Cation Exchange Capacity (Kruskal-Wallis: chi-squared = 10.56, df = 5, p-value = 0.06), plant available P (Kruskal-Wallis: chi-squared = 6.83, df = 5, p-value = 0.23), K ($F_{5,23} = 1.42$, p-value = 0.25) and exchangeable K ($F_{5,23} = 1.43$, p-value = 0.25).

Fig. 3: Range of two important variables (Clay (g/kg) and pH water ratio 1:5) in the NMDS performed on the 29 soil analyses for the 6 types of soil (NMDS stress: 0.045). The coloured curves represent the values of the two variables studied: clay (red) and pH (green).

367
368
369
370
371

Fig. 4: Means and standard error of the different variables studied for each type of soil from the quarries and the steppe (N = 4 or 5). The bars of the histogram with letters in common are not significantly different according to the post-hoc comparisons Tukey HSD tests or Wilcoxon tests with Bonferroni adjustment.

3.3. Relation between type of soil and traces of biological activity

3.3.1. Earthworm activity

Axis 1 (38.36% of inertia) of the MCA performed on the data for presence of earthworms discriminates the soil transfers (reconstituted Technosols) without contact with the phreatic zone from other types of soil (Fig. 5). Soils with no contact with the phreatic zones have an organization similar to that of the original ecosystem but with a higher level of earthworm activity, evidenced by the presence of numerous burrows running in all directions. The other soil transfers show signs of the presence of earthworms but in lower proportions, like in the steppe. They are characterised by the small number of tunnels, mainly nondescript or oblique, reflecting changes in the macrostructure of the soils and / or the distribution of coarse fragments. Hyperskeletal Leptosols and Technosols do not present or have very few tunnels (Fig. 5).

Fig. 5: MCA on the different types of soil with projection of the signs of presence of earthworms (6 types of soil $\times$ 19 descriptions of soil profiles).

3.3.2. Root activity

In the Multiple Component Analysis (MCA), Axis 1 (23.35% of inertia), clearly separates the soil transfers from the Technosols (Fig. 6). In contrast, Axis 2 (19.79% of inertia) discriminates the Technosols from the Hyperskeletic Leptosols. The Technosols present a very small quantity of roots, or even their absence. The small, fine roots have a mainly nondescript orientation. The Hyperskeletic Leptosols present very few roots. They are of intermediate size and vertical orientation. The majority of these roots are also impeded by a physical obstacle resulting in twisted roots compared to those of other soils.

Soils where there was a transfer and whatever the mode (with or without contact with the water table, > 40 cm of sol), present the greatest number of roots of variable or vertical orientation. The roots are healthy and of all sizes (fine, intermediate or large roots) present within the same profile. Finally, these roots deviate very little. The steppe is characterised by a high abundance of intermediate-sized roots, and most often impeded by a physical obstacle owing to the high proportion of pebbles in these soils. These characteristics are also found in the three types of soil transfer (Fig. 6).

Fig. 6: MCA on the different types of soil with projection of the characteristics of the root activity (6 types de soils $\times$ 19 descriptions of soil profiles).

3.4. Soil and plant cover relation

The plant cover differs significantly in the different types of soil in the quarries (Kruskal-Wallis: chi-squared = 55.65, df = 5, p-value <0.05***) (Fig. 7). All the soil transfers are similar to the steppe Cambisol, with more than 60% of plant cover on average per quadrat. In contrast, the Technosols and the Hyperskeletic Leptosols, which do not differ significantly from each other, present more than half as much plant cover in comparison with the other types of soil.

Fig. 7: Vegetation percent cover studied for each type of soil from the quarries and the steppe (N = 4 or 5). The bars of the histogram with letters in common are not significantly different according to the post-hoc comparisons Wilcoxon tests with Bonferroni adjustment.

4. Discussion

It has already been demonstrated that opencast mining entails a high level of variability of the soils (Dimitrakopoulos and Mackie, 2008). The various techniques of excavation and restoration of the sites also give rise to marked heterogeneity in the development of soil biota and vegetation (Chenot et al., 2017; Frouz et al., 2001). Our results confirm that all the soils resulting from the former operation of the quarries present their own specific characteristics but which remain very remote, even in the very long term, from the characteristics of the destroyed Haplic Cambisol (Hyperskeletal Leptosols, Technosols). Pedogenetic processes are very slow or even blocked by the recurrent action of certain environmental parameters (random fluctuation of the water table subjected to artificial irrigation processes in the plain evidenced by observations of hydromorphic stains in soils). The soil transfer operations undertaken under good conditions (same soil thickness as the reference steppe and no contact with the phreatic zone) have on the other hand made possible to restore all the physical and chemical properties recorded in the reference steppe soil in the topsoil (0-40 cm) except for the fine and coarse silt content, and for earthworm and root activity.

The original soil of the areas degraded by the quarries is usually lost in part or totally, leaving only skeletal materials (Kundu and Ghose, 1997; Sheoran et al., 2010; Wong, 2003). In our case, the Haplic Cambisol was replaced by raw geological material, the Durancian pebble on which the Hyperskeletal Leptosols develop, reflecting above all the properties of the outcropping bedrock. It is associated with a loss of the basic structural elements, often with a lack of organic matter and the associated nutrients (Harris et al., 1998) and marked by the strong presence of coarse fragments (>60%) (Baize and Girard, 2008), as evidenced by our results.

In the absence of rehabilitation of these sites after mining ceased, these Hyperskeletal Leptosols persist, and 30 years after their abandonment, very few of these soils have evolved towards soils with a more complex organisation. A beginning of pedogenesis over a few centimetres at the surface was observed following the deposition of leaves at the most heavily wooded sites, in particular by poplars that have become established there. The pedogenetic processes may also be blocked in these soils following the artificial fluctuations of the water table zone itself, associated with the sampling and restitution of waters in relation with the irrigation systems of the fruit orchards (drop by drop) and the hay meadows of La Crau (submersion) (Beltrando, 2015). The shallow depth of the Hyperskeletal Leptosols associated with a harsh pedoclimate, which can be very dry in summer, and the high concentration of pebbles (Jim, 2001) are also a constraint on the root volume of plants, which is thus very limited. The absence of fine particles associated with the domination of dilated pores present in the sandy matrix limit the retention of water necessary to the plants when they are no longer in contact with the phreatic zone. The virtual absence of earthworms and roots in these soils makes them very impoverished and lacking structure and in consequence of poor quality (Hu et al., 1992; Sheoran et al., 2010). In addition, these soils, because of their pseudo-soft consistency and their sandy texture, are very sensitive to erosion and their fine particles may thus be regularly wind eroded by the strong presence of the *Mistral* in this region (Devaux et al., 1983). With regard to the chemical parameters, these soils are also very poorly fertile. The cation exchange capacity and the stocks of essential plant nutrients, in particular nitrogen and phosphorus, are low. These conditions constrain the plant development, and this explains why very low herbaceous plant covers were observed. Even after 30 years of quarry abandonment, these soils remain very remote from the reference Haplic Cambisol and there is no indication to suggest that there might one day be a progression towards this type of soil, given the extent of the degradation (suppression of the fersialitic layer) and the new environmental conditions generated by mining (destruction of the conglomerate and intermittent contact with the phreatic zone, depending on the depth of the quarrying).

These new environmental conditions entail problems with regard to the development and the maintenance of the vegetation at the formerly exploited sites (low plant cover and root activity). The plant cover which develops there has only limited access to nutrients, in particular during periods of drought. The establishment of the vegetation is slow and develops with difficulty, thus limiting the ecological succession, leaving the ecosystem at a pioneer stage (small biomass and rare nutrient content), rather characterised by dry grasslands (Harris et al., 1998; Tomlinson et al., 2008; Walker and Moral, 2003; Wong, 2003). Yuan et al. (2006) have shown that this is more marked by the limited volume of the available soil than by the fertility of the soils. These Hyperskeletal Leptosols are thus considered of poor quality at the agronomic level (Hu et al., 1992; Sheoran et al., 2010). However, at the biological level, many of these habitats are classified as of interest by the European Community (priority habitats according to the European directive), because of the presence of rare species (Baize and Girard, 2008).

After mining ceased, and mainly for safety or landscaping purposes, various rehabilitation measures were undertaken at these sites. They mainly consisted in depositing a wide variety of materials on the Durancian pebbles. They resulted in the development of Technosols when they developed on non-pedological transported materials (mine or quarry spoil, domestic waste, residual sludge, slag, rubble, concrete, asphalt, *etc.*) (Baize and Girard, 2008). The physical and chemical properties of these soils are thus highly heterogeneous and far removed from the reference Haplic Cambisol, as is the vegetation that develops there (poplar or willow forests, wetland water meadows, *etc.*). As on the Hyperskeletal Leptosols, little vegetation develops because of the quality of the materials and the compacting caused by the heavy equipment that deposited these materials. This compacting results in

a loss of soil structure, limits the presence of earthworms, and the development and penetration of roots. Nevertheless, given the more or less distant origin of the materials deposited at the site, the vegetation developing there may be composed of species that are rare at the regional scale (Chenot et al., 2017) and may thus possess a heritage value that should be taken into account in possible future redevelopment planning. In contrast to the Hyperskeletal Leptosols, the dumping of these materials has nonetheless led to the insulation of the topsoil from fluctuations in the water table, giving rise to the development of more xeric soils.

In other cases, there has been rehabilitation with the dumping of soil transfers. These deposits are constituted of fersialitic layers from the arable layers of the site before the start of exploitation, but mixed with each other or with other materials derived from the quarrying (*poudingue* blocks, decantation clays, various kinds of rubble, etc.). This results in reconstituted Technosols. This rehabilitation process involves the succession of various operations: the removal of the surface layers (< 40 cm) down to the puddingstone, its stockpiling, its storage for a variable period of time corresponding to the time of the destruction of the underlying puddingstone and the extraction of the Durancian pebbles (5 to 10 years), its transport and finally its re-spreading at the chosen site. Each of these operations may involve a certain degradation of the physical properties, in particular the leaching of certain fine particles such as the silt in the present case. The structure of the soil may also be degraded, the reduced porosity resulting in poor aeration of the soil, poor drainage and increased resistance to the penetration of roots, which in consequence reduces the plant growth (Baize and Girard, 2008; Bowen et al., 2005; Geissen et al., 2013; Stahl et al., 2002).

This study clearly shows the wide diversity of the soils that have been deposited or have according to the different types of exploitation and rehabilitation been undertaken formerly. If the positive impact of the diversity of certain modes of quarrying have already been demonstrated with regard to the flora (Chenot et al., 2017; Craig et al., 2015; Prach et al., 2013; Vécirin and Muller, 2003), and the fauna (Adamopoulou and Legakis, 2006), few studies have focused on the impact on the diversity of the soils developed relative to the original situation (Jarvis and Walton, 2012).

Thirty years after the rehabilitation process, the reconstituted Technosols present little significant difference with the reference steppe, whatever the physical or chemical parameter measured. They may therefore be characterised as of much better quality for the rehabilitation of the pre-existing steppe type vegetation compared to the Technosols and the Hyperskeletal Leptosols, and in particular for the soil transfer carried out on substrates allowing no contact with the phreatic zone (Chenot et al., 2017). The transferred fersialitic layers present better water retention characteristics than the Hyperskeletal Leptosols or Technosols because of the much lower stone content and the presence of particles of less than 2 mm which improve them (Moreno-de las Heras et al., 2008; Nicolau, 2002; Sheoran et al., 2010). These characteristics allow a better development of the vegetation in these soils. Plant cover of more than 80% has been recorded on these soils as well as extensive root development. The soil transfers thus allow a much faster improvement of the topsoil, in particular due to the earlier establishment of the vegetation (Bulot et al., 2014; Weber et al., 2015) compared to the Hyperskeletal Leptosols. Consequently, the reconstituted Technosols are much closer to the reference soil, at least regarding the topsoil, confirming the results obtained in the short term by Bulot et al. (2017). It has however already been demonstrated in the La Crau plain that the soil transfer had an impact on the content of total nitrogen, organic carbon and the pH, but only in the short term (3 years) (Bulot et al., 2014, 2017). The time that has passed since the rehabilitation may therefore explain the absence of significant differences 30 years after the re-spreading of the soil.

Similarly, the plant cover in the reconstituted Technosols is similar to that of the reference steppe. However, the plant communities are not similar with regard to their specific composition and their structure (Chenot et al., 2017). This might in particular be explained by the non-reestablishment of the whole process of coexistence which governs the structuring of the steppe communities resulting from several thousands of years of sheep grazing and rangeland fires (Henry et al., 2010), but also the not yet differentiated activity of the soil fauna, of which the strong influence on the composition of the vegetation has already been demonstrated (De Deyn et al., 2003). The transferred soils without contact with water thus show more intensive earthworm activity than the other types of transfer. The density of the galleries is much lower in the soils subjected to the fluctuations of the water table (Hyperskeletal Leptosols), constituted of anthropogenic materials (Technosols) or with the deposition of more than 40 cm of earth (Boyer et al., 2011; Geissen et al., 2013). The low earthworm density might thus contribute to the limitation of the development of the plant cover (Frouz et al., 2007; Scullion and Malik, 2000). The presence of earthworms, acting on the soil structure, allows the plants to benefit from more extensive root development and favours access to water and nutrients (Boyer and Wratten, 2010).

Nowadays, the rehabilitation of quarries after the end of exploitation is compulsory (UNEP et al., 2005; UNEP/CBD/COP, 2012). The natural recovery of a site is a long process and it has sometimes been recommended to wait a certain time (several hundred years) studying the natural dynamics before adopting management measures if sites are to be rehabilitated (Letheren, 2009; Rao et al., 2000). However, spontaneous restoration is not foreseeable in the context of global change. It is therefore not considered an acceptable rehabilitation strategy (Cullen et al., 1998). For the rehabilitation of ecosystems and of the ecological functions in a post-mining landscape, reconstructing soils is thus necessary (Jim, 2001). Soil engineering operations should therefore be undertaken (Bradshaw, 1997), except for some specific ecosystems where the question arises whether ecological rehabilitation is really necessary. The formation of the topsoil, that is the organo-mineral layers, affected by the vegetation (source of organic matter) and by the biota of the soil (which transforms the organic matter), is of particular importance. The reconstitution and the management of a layer of soil suited to supporting the vegetation in the long term is thus a crucial phase of ecological rehabilitation. The soil component as limiting factor may frustrate attempts at restoration (Bulot et al., 2017; Jim, 2001).

The most widely used technique and which is considered as the best for rehabilitating the reference ecosystem is soil transfer (Bulot et al., 2017; Fowler et al., 2015). Our results show that in the long term, the replacement of the topsoil by transfer presents characteristics that are virtually similar to those of the steppe topsoil. It is thus a very important operation to take into account for the management of sites post-mining. This technique should be very carefully studied before putting it into operation (depth of excavation, height and duration of stockpiling, conditions of re-spreading, etc.). Serious damage may be done to the soils if they are improperly managed during their reestablishment post-mining (Geissen et al., 2013; Park et al., 2011; Strohmayer, 1999). The main problems likely to occur are the loss of soil structure and excessive compacting (Duncan and Bransden, 1986; Ghose, 2001). This damage may be caused to the soil if the topsoil is removed under humid conditions, or if heavy vehicles are driven over the soil after re-spreading. Even if the replacement of the topsoil would appear to be the best way to rehabilitate mine ecosystems (Fowler et al., 2015; Ghose, 2001; Vécirin and Muller, 2003), various other rehabilitation measures may be proposed. In particular, in the case of absence of original vegetal earth and the excessive cost of importing vegetal earth from elsewhere. In other cases, the topsoil may have lost all its properties and its seed banks when it has been stockpiled for too long and is responsible for the development of weeds which have been trapped by the heaps of soil during stockpiling (Golos and Dixon, 2014;

Jefferson and Usher, 1987; Jones and Esler, 2004). In these cases, debris may even be preferable to the topsoil. For this process, it is recommended to use species adapted to the constraints of the soils and which could colonise them. It has been shown that it is essentially the rapidly developing mycorrhiza and / or nitrogen-fixing species directly sown or planted on the bare substrate that will speed up the pedogenesis of the soils (Bellingham et al., 2001; Brune et al., 2007; Meuser, 2012) and enable the implantation of the desired species (Callaway, 1997, 1995). It has been shown that these species allow an increase in the carbon and nitrogen content of the soil after their installation (Macedo et al., 2008), which would enhance the quality of the soil and put the ecosystem back on the right track towards the reference ecosystem. The choice of species may also focus on the fast-growing pioneer species, giving priority to native species (Bellingham et al., 2001; Parrotta et al., 1997). There is a wide range of rehabilitation recommendations, and it is important to carry out a full analysis of the ecosystem before attempting the rehabilitation of the sites, integrating in particular the description of the soils developed. It should not be overlooked that the ecosystems have a certain resilience and may restore themselves, without human intervention (Bradshaw, 1997). Similarly, active restoration operations (here, soil transfer) should also be assessed in the short term (Bulot et al., 2014, 2017) but also in the very long term in order to integrate the slow pedogenetic processes.

Conclusions

This study confirms that all the soils resulting from the former exploitation modes and rehabilitation of the quarries present their own specific characteristics (upper soil layer fertility, soil profile vertical organization). Moreover they remain very different, even after 30 years, from the characteristics of the Haplic Cambisol of the destroyed reference soil ecosystem. Pedogenetic processes are very slow or even blocked by the recurrent action of some environmental parameters such as the artificial and random fluctuation of the water table. In terms of ecological rehabilitation, only topsoil transfers have allowed to restore most of the physical and chemical properties recorded close to the reference ecosystem soil but only in the soil upper-layer. Nevertheless, this technique must be used in good conditions to reach the restoration objectives: no long topsoil stockpiling, topsoil manipulation in dry conditions, etc.. Soil study is then an indispensable step to understand ecosystem functioning and to optimize ecological rehabilitation efficiency.

Acknowledgements

This study was supported by funding from the company Gagneraud Construction. We thank the *Réserve Naturelle Nationale des Coussous de Crau* and the *Grand Port Maritime de Marseille* at Fos-sur-Mer for permission to access the study sites. We thank Pierre Bourguet and Jean-Marc Arnal (*Société des Carrières de La Ménudelle*) for their collaboration with regard to the early exploitation of quarries. We are also grateful to our PhD students and our technician for assistance with the field work, analyses and general reflection: Anne Aurière, Cannelle Moinardeau, Hervé Ramone.

Bibliographical references

- Adamopoulou, C., Legakis, A., 2006. Using reptiles and soil arthropods as indicators for open quarry restoration in Mediterranean-type ecosystems. Presented at the 10th Intern. Congr. on the Zoogeography and Ecology of Greece and adjacent regions, Book of abstracts, Patras, Greece, p. 6.
- Allison, L.E., 1965. Organic carbon, in: Black, C.A., Evans, D.D., White, J.L., Ensminger L.E., & Clark, F.E., 1965. Methods of Soil Analysis. American Society of Agronomy, Madison, Wisconsin, pp. 1372–1378.
- Baize, D., Girard, M.C., 2008. Référentiel pédologique 2008 - AFES (Association Française pour l'Etude du Sol). Editions Quae.

- Baize, D., Jabiol, B., 2011. Guide pour la description des sols. Éd. Quae, Versailles.
- Bellingham, P.J., Walker, L.R., Wardle, D.A., 2001. Differential facilitation by a nitrogen-fixing shrub during primary succession influences relative performance of canopy tree species. *Journal of Ecology* 89, 861–875. doi:10.1046/j.0022-0477.2001.00604.x
- Beltrando, G., 2015. La plaine de la Crau (ouest de la Provence), un territoire aux enjeux socio-économiques et écologiques en mutation. *Cybergeo: European Journal of Geography*. doi:10.4000/cybergeo.27356
- Bonferroni, C.E., 1936. Teoria statistica delle classi e calcolo delle probabilità. *Pubblicazioni del R Istituto Superiore di Scienze Economiche e Commerciali di Firenze* 8, 1–62.
- Bourrelly, M., Borel, L., Devaux, J.P., Louis-Pluel, J., Archiloque, A., 1983. Dynamique annuelle et production primaire nette de l'écosystème steppique de Crau (Bouches du Rhône). *Biologie et écologie méditerranéenne*.
- Bouteyre, G., Duclos, G., 1994. Carte pédologique de France à 1/100 000 - Arles. Notice explicative de la carte, Service d'Étude des Sols et de la Carte Pédologique de France. ed. Centre de Recherches d'Orléans, Olivet.
- Bowen, C.K., Schuman, G.E., Olson, R.A., Ingram, J., 2005. Influence of Topsoil Depth on Plant and Soil Attributes of 24-Year Old Reclaimed Mined Lands. *Arid Land Research and Management* 19, 267–284. doi:10.1080/15324980590951441
- Boyer, S., Wratten, S., Pizey, M., Weber, P., 2011. Impact of soil stockpiling and mining rehabilitation on earthworm communities. *Pedobiologia*, 9th International Symposium on Earthworm Ecology Xalapa, Veracruz, Mexico, 5th – 10th September 2010 54, Supplement, S99–S102. doi:10.1016/j.pedobi.2011.09.006
- Boyer, S., Wratten, S.D., 2010. The potential of earthworms to restore ecosystem services after opencast mining – A review. *Basic and Applied Ecology* 11, 196–203. doi:10.1016/j.baae.2009.12.005
- Bradshaw, A., 1997. Restoration of mined lands—using natural processes. *Ecological Engineering* 8, 255–269. doi:10.1016/S0925-8574(97)00022-0
- Bradshaw, A.D., Hüttel, R.F., 2001. Future minesite restoration involves a broader approach. *Ecological Engineering* 17, 87–90. doi:10.1016/S0925-8574(00)00149-X
- Bremner, J.M., 1996. Nitrogen-Total, in: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., & Sumner, M.E., 1996. *Methods of Soil Analysis. Part 3 – Chemical Methods*. Soil Science Society of America Book Series, pp. 1085–1121.
- Brune, B., Domergue, O., Maure, L., Brahic, P., Galiana, A., Josa, R., De lajudie, P., Attallah, T., Risk, H., El-Hajj, S., Cleyet-Marel, J.-C., 2007. Potential of nitrogen-fixing symbiotic systems for revegetation strategies of degraded land sites in Mediterranean conditions. *Cah. Agric.* 16, 324–329. doi:10.1684/agr.2007.0116
- Buisson, E., Dutoit, T., 2006. Creation of the natural reserve of La Crau: Implications for the creation and management of protected areas. *Journal of Environmental Management* 80, 318–326. doi:10.1016/j.jenvman.2005.09.013
- Bulot, A., Potard, K., Bureau, F., Bérard, A., Dutoit, T., 2017. Ecological restoration by soil transfer: impacts on restored soil profiles and topsoil functions. *Restor Ecol* 25, 354–366. doi:10.1111/rec.12424
- Bulot, A., Provost, E., Dutoit, T., 2014. A comparison of different soil transfer strategies for restoring a Mediterranean steppe after a pipeline leak (La Crau plain, South-Eastern France). *Ecological Engineering* 71, 690–702. doi:10.1016/j.ecoleng.2014.07.060
- Callaway, R.M., 1997. Positive interactions in plant communities and the individualistic-continuum concept. *Oecologia* 112, 143–149. doi:10.1007/s004420050293

- Callaway, R.M., 1995. Positive interactions among plants. *Bot. Rev* 61, 306–349.
doi:10.1007/BF02912621
- Chenot, J., Jaunatre, R., Buisson, E., Dutoit, T., 2017. Long-term effects of topsoil transfer assessed thirty years after rehabilitation of dry alluvial quarries in Southeastern France. *Ecological Engineering* 99, 1–12. doi:10.1016/j.ecoleng.2016.11.010
- Chessel, D., Dufour, A.-B., Thioulouse, J., 2004. The ade4 package - I : One-table methods. *R News* 4, 5–10.
- Ciesielski, H., Sterckeman, T., Santerne, M., Willery, J.P., 1997. A comparison between three methods for the determination of cation exchange capacity and exchangeable cations in soils. *Agronomy for Sustainable Development* 17, 9–15. doi:10.1051/agro:19970102
- Commission de Pédologie et de Cartographie des Sols, 1967. Classification des sols.
- Craig, M., Buckley, P., Howell, R., 2015. Responses of an ancient woodland field layer to soil translocation: methods and timing. *Appl Veg Sci* 18, 579–590. doi:10.1111/avsc.12170
- Cullen, W.R., Wheeler, C.P., Dunleavy, P.J., 1998. Establishment of species-rich vegetation on reclaimed limestone quarry faces in Derbyshire, UK. *Biological Conservation* 84, 25–33. doi:10.1016/S0006-3207(97)00089-X
- Dana, E.D., Mota, J.F., 2006. Vegetation and soil recovery on gypsum outcrops in semi-arid Spain. *Journal of Arid Environments* 65, 444–459. doi:10.1016/j.jaridenv.2005.08.009
- De Deyn, G.B., Raaijmakers, C.E., Zoomer, H.R., Berg, M.P., de Ruiter, P.C., Verhoef, H.A., Bezemer, T.M., van der Putten, W.H., 2003. Soil invertebrate fauna enhances grassland succession and diversity. *Nature* 422, 711–713. doi:10.1038/nature01548
- Devaux, J.P., Archiloque, A., Borel, L., Bourrelly, M., Louis-Palluel, J., 1983. Notice de la carte phyto-écologique de la Crau (Bouches du Rhône). *Biologie et écologie méditerranéenne* 10, 5–54.
- Dimitrakopoulos, R., Mackie, S., 2008. Joint Simulation of Mine Spoil Uncertainty for Rehabilitation Decision Making, in: Soares, A., Pereira, M.J., Dimitrakopoulos, R. (Eds.), *GeoENV VI – Geostatistics for Environmental Applications, Quantitative Geology and Geostatistics*. Springer Netherlands, pp. 349–359. doi:10.1007/978-1-4020-6448-7_29
- DITR, 2005. Mine Closure and Completion: Leading Practice Sustainable Development Program for the Mining Industry, Australian Government. ed. Department of Industry Tourism and Resources, Canberra.
- Dray, S., Dufour, A.-B., 2007. The ade4 Package: Implementing the Duality Diagram for Ecologists. *Journal of Statistical Software* 1–20.
- Dray, S., Dufour, A.B., Chessel, D., 2007. The ade4 Package--II: Two-table and K-table Methods. *R News* 7, 47–52.
- Dumas, J., 1831. Procédés de l'analyse organique. *Annal. Chem. Phys.* 198–213.
- Duncan, N.A., Bransden, B.E., 1986. The effects on a restored soil caused by soil moving under different moisture contents. *Applied Geography* 6, 267–273. doi:10.1016/0143-6228(86)90006-8
- Duque, J.F.M., Pedraza, J., Díez, A., Sanz, M.A., Carrasco, R.M., 1998. A geomorphological design for the rehabilitation of an abandoned sand quarry in central Spain. *Landscape and Urban Planning* 42, 1–14. doi:10.1016/S0169-2046(98)00070-X
- European Parliament, 2014. Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment.
- Falipou, P., Legros, J.P., 2002. Le système STIPA-2000 d'entrée et édition des données pour la base nationale de sols DONESOL II. *Etude et Gestion des Sols* 9, 55–70.

- Fowler, W.M., Fontaine, J.B., Enright, N.J., Veber, W.P., 2015. Evaluating restoration potential of transferred topsoil. *Appl Veg Sci* 18, 379–390. doi:10.1111/avsc.12162
- Frouz, J., Keplin, B., Pižl, V., Tajovský, K., Starý, J., Lukešová, A., Nováková, A., Balík, V., Háněl, L., Materna, J., Düker, C., Chalupský, J., Rusek, J., Heinkele, T., 2001. Soil biota and upper soil layer development in two contrasting post-mining chronosequences. *Ecological Engineering* 17, 275–284. doi:10.1016/S0925-8574(00)00144-0
- Frouz, J., Pižl, V., Tajovský, K., 2007. The effect of earthworms and other saprophagous macrofauna on soil microstructure in reclaimed and un-reclaimed post-mining sites in Central Europe. *European Journal of Soil Biology* 43, Supplement 1, S184–S189. doi:10.1016/j.ejsobi.2007.08.033
- Geissen, V., Wang, S., Oostindie, K., Huerta, E., Zwart, K.B., Smit, A., Ritsema, C.J., Moore, D., 2013. Effects of topsoil removal as a nature management technique on soil functions. *CATENA* 101, 50–55. doi:10.1016/j.catena.2012.10.002
- Ghose, M., 2001. Management of topsoil for geo-environmental reclamation of coal mining areas. *Env Geol* 40, 1405–1410. doi:10.1007/s002540100321
- Golos, P.J., Dixon, K.W., 2014. Waterproofing Topsoil Stockpiles Minimizes Viability Decline in the Soil Seed Bank in an Arid Environment. *Restor Ecol* 22, 495–501. doi:10.1111/rec.12090
- Hadley, W., Winston, C., 2016. Package “devtools”: Tools to Make Developing R Packages Easier. R package version 1.12.0 63.
- Harris, J.A., Birch, P., Palmer, J.P., 1998. *Land restoration and reclamation: principles and practice*, Reprinted. ed. Addison Wesley Longman, Harlow.
- Heneghan, L., Miller, S.P., Baer, S., Callahan, M.A., Montgomery, J., Pavao-Zuckerman, M., Rhoades, C.C., Richardson, S., 2008. Integrating Soil Ecological Knowledge into Restoration Management. *Restoration Ecology* 16, 608–617. doi:10.1111/j.1526-100X.2008.00477.x
- Henry, F., Talon, B., Dutoit, T., 2010. The age and history of the French Mediterranean steppe revisited by soil wood charcoal analysis. *The Holocene* 20, 25–34. doi:10.1177/0959683609348841
- Hu, Z., Caudle, R.D., KXhong, S., 1992. Evaluation of farmland reclamation effectiveness based on reclaimed mine soil properties. *International Journal of Surface Mining, Reclamation and Environment* 6, 129–135. doi:10.1080/09208119208944327
- Husson, F., Josse, J., Le, S., Mazet, J., 2016. Package ‘FactoMineR’: Multivariate Exploratory Data Analysis and Data Mining. R package version 1.33 96.
- IUSS Working Group WRB, 2015. World reference base for soil resources 2014: international soil classification system for naming soils and creating legends for soil maps., *World Soil Resources Reports*. ed. FAO, Rome.
- Jarvis, D., Walton, G., 2012. So you have no soil for quarry restoration? pp. 160–165, in: Hunger, E. and Walton, G. (Eds.) *Proceedings of the 16th Extractive Industry Geology Conference*, EIG Conferences Ltd. p. 194.
- Jefferson, R.G., Usher, M.B., 1987. The seed bank in soils of disused chalk quarries in the yorkshire wolds, England: Implications for conservation management. *Biological Conservation* 42, 287–302. doi:10.1016/0006-3207(87)90073-5
- Jim, C.Y., 2001. Ecological and Landscape Rehabilitation of a Quarry Site in Hong Kong. *Restoration Ecology* 9, 85–94. doi:10.1046/j.1526-100x.2001.009001085.x
- Jones, F.E., Esler, K.J., 2004. Relationship between soil-stored seed banks and degradation in eastern Nama Karoo rangelands (South Africa). *Biodiversity and Conservation* 13, 2027–2053. doi:10.1023/B:BIOC.0000040007.33950.38
- Koch, J.M., 2007. Restoring a Jarrah Forest Understorey Vegetation after Bauxite Mining in Western Australia. *Restoration Ecology* 15, S26–S39. doi:10.1111/j.1526-100X.2007.00290.x

782 Kundu, N.K., Ghose, M., 1997. Soil profile Characteristic in Rajmahal Coalfield area. *Indian Journal*
783 *of Soil Conservation* 25, 28–32.

784 Lavelle, P., Bignell, D., Lepage, M., Wolters, V., Roger, P.-A., Ineson, P., Heal, O.W., Dhillon, S.,
785 1997. Soil function in a changing world: the role of invertebrate ecosystem engineers.
786 *European Journal of Soil Biology* 33, 159–193.

787 Letheren, B., 2009. Ecological restoration of sandstone quarry sites: A systematic review of literature.
788 School of the Environment and Natural Resources, Bangor University, UK.

789 Macedo, M.O., Resende, A.S., Garcia, P.C., Boddey, R.M., Jantalia, C.P., Urquiaga, S., Campello,
790 E.F.C., Franco, A.A., 2008. Changes in soil C and N stocks and nutrient dynamics 13 years
791 after recovery of degraded land using leguminous nitrogen-fixing trees. *Forest Ecology and*
792 *Management* 255, 1516–1524. doi:10.1016/j.foreco.2007.11.007

793 Metson, A.J., 1956. Methods of chemical analysis for soil survey samples. New Zealand Department
794 of Scientific and Industrial Research.

795 Meuser, H., 2012. Soil Remediation and Rehabilitation: Treatment of Contaminated and Disturbed
796 Land. Springer Science & Business Media.

797 Moreno-de las Heras, M., Nicolau, J.M., Espigares, T., 2008. Vegetation succession in reclaimed coal-
798 mining slopes in a Mediterranean-dry environment. *Ecological Engineering* 34, 168–178.
799 doi:10.1016/j.ecoleng.2008.07.017

800 Neuwirth, E., 2014. Package “RColorBrewer”: ColorBrewer Palettes. R package version 1.1-2 5.

801 Nicolau, J.-M., 2002. Runoff generation and routing on artificial slopes in a Mediterranean–
802 continental environment: the Teruel coalfield, Spain. *Hydrol. Process.* 16, 631–647.
803 doi:10.1002/hyp.308

804 Oksanen, J.F., Blanchet, G., Kindt, R., Legendre, P., Minchin, P.R., O’Hara, R.B., Simpson, G.L.,
805 Solymos, P., Henry, M., Stevens, H., Wagner, H., 2015. Package ‘vegan’: Community
806 Ecology Package. R package version 2.3-2 285.

807 Olsen, S.R. (Sterling R., 1954. Estimation of available phosphorus in soils by extraction with sodium
808 bicarbonate. Washington, D.C. : U.S. Dept. of Agriculture.

809 Park, S.-G., Yi, M.-H., Shin, H.-T., Kurosawa, K., 2011. Temporal Change of Soil Animals of the
810 Stockpiled Forest Topsoil in Relation to Soil Temperature and Soil Moisture. *Journal of the*
811 *Faculty of Agriculture, Kyushu University* 56, 9–13.

812 Parrotta, J.A., Turnbull, J.W., Jones, N., 1997. Catalyzing native forest regeneration on degraded
813 tropical lands. *Forest Ecology and Management* 99, 1–7. doi:10.1016/S0378-1127(97)00190-4

814 Pérès, G., Vandenbulcke, F., Guernion, M., Hedde, M., Beguiristain, T., Douay, F., Houot, S., Piron,
815 D., Richard, A., Bispo, A., Grand, C., Galsomies, L., Cluzeau, D., 2011. Earthworm indicators
816 as tools for soil monitoring, characterization and risk assessment. An example from the
817 national Bioindicator programme (France). *Pedobiologia*, 9th International Symposium on
818 *Earthworm Ecology* Xalapa, Veracruz, Mexico, 5th – 10th September 2010 54, Supplement,
819 S77–S87. doi:10.1016/j.pedobi.2011.09.015

820 Prach, K., Lencová, K., Řehouňková, K., Dvořáková, H., Jírová, A., Konvalinková, P., Mudrák, O.,
821 Novák, J., Trnková, R., 2013. Spontaneous vegetation succession at different central European
822 mining sites: a comparison across seres. *Environ Sci Pollut Res* 20, 7680–7685.
823 doi:10.1007/s11356-013-1563-7

824 R Development Core Team, 2016. R: A Language and Environment for Statistical Computing.
825 Reference Index. R Foundation for Statistical Computing, Vienna, Austria.

826 Rao, A.V., Tarafdar, J.C., Tak, R., 2000. Improvement in the microbiological productivity of
827 limestone mine spoils with time. *Agrochimica* 44, 171–179.

- Römermann, C., Tackenberg, O., Poschlod, P., 2005. How to predict attachment potential of seeds to sheep and cattle coat from simple morphological seed traits. *Oikos* 110, 219–230. doi:10.1111/j.0030-1299.2005.13911.x
- Scullion, J., Malik, A., 2000. Earthworm activity affecting organic matter, aggregation and microbial activity in soils restored after opencast mining for coal. *Soil Biology and Biochemistry* 32, 119–126. doi:10.1016/S0038-0717(99)00142-X
- Sheoran, V., Sheoran, A., Poonia, P., 2010. Soil Reclamation of Abandoned Mine Land by Revegetation: A Review. *International Journal of Soil, Sediment and Water* 3.
- Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P., Tabatabai, M.A., Johnston, C.T., Sumner, M.E., 1996. Methods of soil analysis. Part 3 - chemical methods. 1390.
- Stahl, P.D., Perryman, B.L., Sharmasarkar, S., Munn, L.C., 2002. Topsoil Stockpiling Versus Exposure to Traffic: A Case Study on In situ Uranium Wellfields. *Restoration Ecology* 10, 129–137. doi:10.1046/j.1526-100X.2002.10114.x
- Strohmayer, P., 1999. Soil Stockpiling for Reclamation and Restoration activities after Mining and Construction.
- Tatin, L., Wolff, A., Boutin, J., Colliot, E., Dutoit, T., 2013. *Écologie et conservation d'une steppe méditerranéenne: La plaine de Crau*. Editions Quae.
- Thomas, G.W., 1996. Soil pH and Soil Acidity, in: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., & Sumner, M.E., 1996. Methods of Soil Analysis Part 3 - Chemical Methods. Soil Science Society of America Book Series, pp. 475–490.
- Tomlinson, S., Matthes, U., Richardson, P.J., Larson, D.W., 2008. The ecological equivalence of quarry floors to alvars. *Applied Vegetation Science* 11, 73–82. doi:10.1111/j.1654-109X.2008.tb00206.x
- UNEP, UNDP, OSCE, NATO, 2005. Mining for Closure: Policies and Guide-lines for Sustainable Mining Practice and Closure of Mines. United Nations Environment Programme (UNEP), United Nations Development Programme(UNDP), Organization for Security and Co-operation in Europe (OSCE) and North Atlantic Treaty Organization (NATO). Europe 97.
- UNEP/CBD/COP, 2012. Convention on Biological Diversity. Decision XI/16: Ecosystem restoration.
- Van-Camp, L., Bujarrabal, B., Gentile, A.R., Jones, R.J.A., Montanarella, L., Olazabal, C., Selvaradjou, S.-K., 2004. Reports of the Technical Working Groups Established under the Thematic Strategy for Soil Protection. EUR 21319 EN/1, Office for Official Publications of the European Communities, Luxembourg.
- Vécrin, M. p., Muller, S., 2003. Top-soil translocation as a technique in the re-creation of species-rich meadows. *Applied Vegetation Science* 6, 271–278. doi:10.1111/j.1654-109X.2003.tb00588.x
- Walker, L.R., Moral, R. del, 2003. Primary Succession and Ecosystem Rehabilitation. Cambridge University Press.
- Weber, J., Strączyńska, S., Kocowicz, A., Gilewska, M., Bogacz, A., Gwiżdż, M., Debicka, M., 2015. Properties of soil materials derived from fly ash 11 years after revegetation of post-mining excavation. *CATENA* 133, 250–254. doi:10.1016/j.catena.2015.05.016
- Whalley, W.R., Dexter, A.R., 1994. Root development and earthworm movement in relation to soil strength and structure. *Archives of Agronomy and Soil Science* 38, 1–40. doi:10.1080/03650349409365834
- Wong, M.H., 2003. Ecological restoration of mine degraded soils, with emphasis on metal contaminated soils. *Chemosphere* 50, 775–780. doi:10.1016/S0045-6535(02)00232-1
- Yuan, J.-G., Fang, W., Fan, L., Chen, Y., Wang, D.-Q., Yang, Z.-Y., 2006. Soil Formation and Vegetation Establishment on the Cliff Face of Abandoned Quarries in the Early Stages of

875 Natural Colonization. Restoration Ecology 14, 349–356. doi:10.1111/j.1526-
876 100X.2006.00143.x
877

878 Appendix A. Modes and factors measured for the traces of animal and plant biological activity in the
879 20 profiles describe (Falipou and Legros, 2002)
880

Biological compartment studied	Modes	Factors
Earthworms	Density	<ul style="list-style-type: none"> - No burrows - Few burrows (1-3/dm²) - Numerous burrows (3-5/dm²) - Very numerous burrows (>5/dm²)
	Orientation	<ul style="list-style-type: none"> - Vertical - Layertal - Oblique - Variable
Roots	Abundance	<ul style="list-style-type: none"> - No roots - Very few (<8/dm²) - Few (8-16/dm²) - Numerous (16-32/dm²) - Very numerous (>32/dm²)
	Localisation	<ul style="list-style-type: none"> - Within the mass - In the aggregates - Between the aggregates - In the crevices - Avoiding compacted zones
	Orientation	<ul style="list-style-type: none"> - Vertical - Nondescript - Oblique - Variable
	State	<ul style="list-style-type: none"> - Healthy - Necrosed - Rotten - Rust-stained
	Dimension	<ul style="list-style-type: none"> - Very fine (<0.5 mm) - Fine (0.5 to 2 mm) - Intermediate (2 to 5 mm) - Large (5 to 20 mm) - Very large (> 20 mm)
	Form	<ul style="list-style-type: none"> - Normal - Twisted - Fishbone - Flat - Change of direction
	Penetration	<ul style="list-style-type: none"> - Non-deviated - Impeded by a physical obstacle - Impeded by a chemical obstacle

881