This is the **accepted version** of the article:

Carabassa, Vicenç; Ortiz Perpiñà, Oriol; Alcañiz, Josep M. «RESTO-QUARRY: indicators for self-evaluation of ecological restoration in open-pit mines». Ecological indicators, Vol. 102 (July 2019), p. 437-445. DOI 10.1016/j.ecolind.2019.03.001

Title: RESTOQUARRY: indicators for self-evaluation of ecological restoration in open-pit mines

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Abstract

Several methods and criteria to evaluate and assess quarry restoration are available in the scientific literature, but they are very specialized and time consuming. Furthermore, there is a lack of evaluation tools appropriate for technicians involved in these types of activities, such as quarry engineers, restoration managers and quality control supervisors in public administration. The work presented attempts to bridge the gap between scientific knowledge and practical needs by proposing a simplified methodology (RESTOQUARRY protocol), which enables the non-scientific public to evaluate restored areas. This procedure focused on five groups of parameters for zone (homogeneous portions within the whole restored area) evaluation: geotechnical risk, drainage network, erosion and physical degradation, soil quality and vegetation status and functionality. Moreover, three groups of parameters are proposed for area (whole restoration) evaluation: landscape integration, ecological connectivity and fauna, and anthropic impacts. This protocol has been tested in 55 open-pit mines located throughout Catalonia (NE Iberian Peninsula), covering a wide range of Mediterranean climatic conditions and geological substrates. Results indicate that the proposed methodology is suitable for detecting critical parameters that can determine the success of the restoration.

Keywords: Open-pit mines reclamation; quarry rehabilitation; ecological restoration; restoration evaluation; ecological indicators

Highlights

A new multicriterial procedure for integrated self-evaluation of mine restorations

It includes ecological, technical and socio-cultural aspects

It uses 34 evaluation parameters, selected and weighted by an expert panel

The evaluation allows to score the whole restoration

The score is accompanied by an interpretation of the monitoring values

The evaluation allows to highlight critical factors for restoration success

1. Introduction

Ecological restoration is defined by The International Society for Ecological Restoration as the process of assisting the recovery of an ecosystem that has been degraded, damaged or destroyed (Clewell et al., 2004), in order to retrieve its environmental functions and ecosystem services. This institution provides a list of ecosystem attributes as a guideline for measuring restoration success after human-induced perturbations. However, what characterizes successful restoration and how best to measure it generates debate among members within the scientific community (Wortley et al., 2013; Crouzeilles et al. 2016). Many methods to evaluate these attributes are available in the scientific literature and most studies are focused on vegetation composition and structure, biodiversity and ecological processes (Ruiz-Jaen & Aide, 2005; Wortley et al. 2013). In the present paper, the concept of restoration is used in a broad sense, including rehabilitation and other recovering alternatives of mined sites.

It is well known that advances in restoration ecology are intrinsically linked to advances in the ecological understanding of the ecosystems to be restored, and the knowledge of soil and vegetation properties is an appropriated way to guarantee restoration success (Prach, 2003; Temperton et al. 2004; Valladares and Gianoli, 2007). Moreover, geotechnical stability, runoff control, landscape integration, and ecological connectivity, among others, are basic site attributes to be considered for a good quality restoration, especially in mining activities. However, the choice of relevant evaluation attributes depends on the type of degradation processes that previously affected the restored zones. Specifically, sites affected by mining activities, such as quarries, are a paradigmatic case of drastic anthropic perturbation, as almost all the components and attributes of the original ecosystem have been destroyed and, therefore, must be restored.

Practitioners have asked researchers to provide potentially useful procedures based on objective indicators (Clewel & Rieger, 1997; Beier et al. 2017). On the other hand, researchers have appointed the need to improve the evaluation of restorations carried out in open-pit mines (Halldórsson et al. 2012, Hagen et al. 2013; Suding 2011), although the available information on the topic has increased in the last years (Wortley et al. 2013). Evaluation tends to be focused on the descriptive characterization of the restored areas, and restricted to a single or few checks after the restoration works (Suding 2011). Nonetheless, a continuous monitoring during all the restoration process is necessary (Allen et al. 2002; Pander and Geist 2013) and should be coupled to the exploitation works. In any case, economic and ecological results of the restoration could be improved if clearer evaluation protocols exist, which also could facilitate the transfer of valuable information to other projects (Nilsson et al. 2015).

The present work attempts to satisfy these demands for evaluating restoration of mine sites, providing a scientifically based multifactorial methodology to be incorporated in the decision-making process. This will lead to regaining the restoration bonds (financial guarantee) that mine companies must deposit in many countries, in order to guarantee the correct restoration of the degraded land. This study aims to contribute to the generation of best available techniques in this field, filling the gap that already exists in the extractive activities sector with an innovative methodology that takes into account a wide range of geotechnical and ecological indicators. Some authors have proposed similar procedures for rangelands and mine sites (Courtney et al. 2010; Dzwonko and Loster 2007; Tongway and Hindley, 2004); however, these methodologies are rather inaccessible to the non-scientific public, as they assess excessively specific or technical indicators. In order to avoid these limitations, RESTOQUARRY protocol, a self-evaluation procedure of open-pit mines restoration, is proposed (Carabassa et al. 2010; Carabassa et al. 2015). This protocol is aimed to be useful for mining engineers and managers of environmental agencies, who can easily put it into practice without having to have much scientific knowledge about ecological restoration. If this goal is reached, better involvement by extractive companies in the restoration process would also be achieved and, therefore, the quality of the restorations carried out by these industries would rise. Moreover, the application of participatory methodologies such as the proposed in this work would aid the cooperation and communication between public administration and extractive industries, which is crucial for improving restoration and finding the most appropriate solution on a case by case basis.

2. Materials and methods

2.1 Selection of restoration indicators

A preliminary proposal of quality indicators/parameters of mining restoration success was subjected to a screening process by experts. This proposal has been based on the know-how generated in previous research projects and carried outwith the collaboration of engineers of mining industries, technicians of competent authorities, ecologists from NGOs, technicians from consulting companies and scientists with broad experience in mine restoration. These actors constituted an expert panel including 17 people/entities. After an independent review process, the first proposal of indicators was made. This proposal included specific indicators applicable to homogeneous zones within the whole area (zone indicators), and a set of more generalist indicators, applicable to the whole restored area (area indicators). This distinction between *area* and *zone* was made in order to correctly evaluate parameters that must be measured separately at slope, habitat or landscape level.

There are five groups of zone indicators: geotechnical risk, drainage network, erosion/degradation processes, soil and vegetation (Table 1). Some vegetation indicators (plant cover, woody species richness and density, or herbaceous species richness) are based on the comparison to a reference site, usually located in an undisturbed zone close to the mine. For geotechnical risk (area affected by landslides and fallen blocks) and erosion (area affected by rill erosion) indicators, the area influenced by instability processes could measured directly at the field or by photointerpretation, depending on the magnitude of the process. Soil bulk density is measured by the excavation method as coarse particles are often abundant in this kind of substrates. Soil sampling is performed using Edelman auger or similar tool to extract the first 20 cm of topsoil. The recommended sampling density is specified in the protocol (20 holes/ha). Vegetation measures are obtained on 10x10 m square plots, distributed along the evaluated zones, and on 10 m transects delimited by the sides of these plots (horizontal and perpendicular to the slope).

Indicators related to the area evaluation are mainly qualitative (see Table 2). This is especially true for the case of landscape integration, where the proposed indicators are based mainly on the perception of the evaluator. However, the protocol gives guidance in order to reduce the subjectivity of the observations, allowing the evaluator to classify landscape integration according to the similarity of the restored area to the surrounding natural landscape. All the methods for measuring the indicators are standardized and explained in Carabassa et al. (2015), including sampling density and recommendable sampling period.

2.2 Transformation of indicators to restoration quality indexes

In order to compare and integrate the evaluation data through a set of individual indicators, the use of functional curves is proposed (Figure 1). The objective is to obtain a global Restoration Quality Index (RQI) that summarizes the main factors influencing the restoration, using the proximity to target methodology (Rodríguez-Loinaz et al. 2015, Roces-Díaz et al. 2018). A functional curve for each parameter is proposed, according to the bibliographyand the knowledge and expertise of the panel members (Cortina et al., 2012; Deltoro et al., 2012, Jorba et al., 2010, Carabassa et al. 2010; Moreno-de las Heras et al., 2008, Alcañiz et al., 2008; Tongway and Hindley, 2004; Conesa, 2003, Forman, 2003). These functions transform each parameter value, measured in its own units, to its respective Restoration Quality units (RQ_x), which are standardized, dimensionless and fully comparable, where 1 represents the maximum quality for restoration and 0 the worst case.

2.3 Indicators weighting

The expert panel was invited to weight the indicators in order of importance for the evaluation of the restoration success. Indicators were weighted using a pairwise comparison method through a Delphi process (Okoli and Pawlowski, 2004; Mukherjee et al 2015). The result of the ranking and pairwise successive comparisons gave a weight (W) for each indicator according to its importance for the whole restoration success. The global restoration quality index (RQI) was calculated as the sum of all the RQ_x multiplied by its respective W:

$$RQI = \sum_{x=m}^{n} (RQ_x \cdot W_x)$$

2.4 Study sites

The RESTOQUARRY protocol was assayed in a pilot test on 55 selected open-pit mines distributed along NE Iberian Peninsula (Catalonia, Spain), covering different climatic conditions, geological substrates, soil types and extraction procedures (Figure 2, Table 3). A total of 106 restored zones were evaluated in these mines applying the proposed methodology.

The selected restored mine-zones of the pilot test included a broad range of restoration goals, landscape type and age. The main restoration goal in this selection was the ecological restoration, but also there were cases of conversion to agriculture and forestry plantations. The surface of the evaluated areas ranged between 0.8 and 165 ha. The trial areas had been restored between 4 and 21 years before the evaluation process, which allowed the comparison of old restorations with new ones.

3. Results

3.1 Zone evaluation

3.1.1. Geotechnical risks

Flat zones and steep slopes (30-37º) were the predominant geomorphologies in the selected restorations. The slope is an important factor that determines geotechnical risks, soil degradation processes, and vegetation establishment. In terms of geotechnical risk, fallen blocks were observed in 60% of the banks with a slope higher than 8º. Fallen blocks represented big stones or boulders (> 20 cm diameter) that had fallen down from extremely steeped slopes (>45º) and/or vertical walls, representing a safety risk and compromising the vegetation located on the trajectory of this fall. Landslides are also related to slope, and a third of the zones with a slope higher than 8º showed this type of geotechnical risk. Moreover, other geotechnical risks, such as subsidences or cracks were also detected, but they affected minor surfaces and in low grade.

3.1.2. Erosion and physical degradation

Regarding soil degradation processes observed, rill erosion was the most relevant. Rill erosion is a concentrated water erosion process that supposes an important soil loss and that could trigger the destabilization of the entire slope. Approximately half of the areas with slopes of more than 30º showed rills with a depth greater than 5 cm. Areas degraded by concentrated water erosion ranged between 1,053 to 40,700 m^2, which represents 4 to 100% of the surface of the restored zones. The calculated erosion rates ranged between 0.2 to 27 Mg ha^{-1} y^{-1} in the affected zones. The slope is also an important factor for sheet water flow as 61% of the zones with a slope greater than 30º were degraded by sheet erosion. Moreover, a quarter of the evaluated zones showed surface crusts as a consequence of splash. Soil compaction and subsurface erosion impacted 20% and 9% of the evaluated zones, respectively.

3.1.3. Soil quality

Organic matter content, electrical conductivity, available phosphorous (P), total nitrogen (N) content and soil depth seemed to be the most limiting factors in the evaluated soils (see Table 4). Poor organic matter contents (<0.8%) were detected in four of the analyzed soils, mainly in the sandy ones. Moderate to high conductivity was detected in some of the soils, but in most of the cases, this was not attributable to the mining activities. A quarter of the soils evaluated showed a low available P content while 12% of the soils showed high levels due to organic amendments (compost, sewage sludge, or pig slurry). This trend was similar to the observed for total N content. Zones with severe slope (>30º) showed an average soil depth of 0.2 m (due to the difficulty of stabilizing topsoil).

3.1.4. Vegetation status and functionality

The herbaceous cover was dominant in the evaluated zones with an average value of 55%, while mean total plant cover (including trees and bushes) was 73%. Plant cover is an important factor to prevent soil losses because erosion problems are mainly detected in zones with <40% of soil surface covered by plants. Bushy invasive species, such as *Arundo donax*, were present in 19% of the evaluated zones. However, these species were not extensively distributed and were found in small patches. In 81% of the evaluated zones, native bushy species were identified. Reproductively mature bushes were observed in 54% of the locations, and spontaneous reproduction of these species were observed in 45% of the cases, mainly corresponding to *Santolina chamaecyparissus* and *Dittrichia viscosa*. Regarding tree species, low canopy cover and diversity were observed as only 17% of the zones had more than three tree species. *Pinus halepensis*, which was widely planted for reforestation in the Mediterranean region due to its resistance to drought and soil deficiencies, was the dominant species. The mortality rate of planted trees was high for native *Quercus* species, reaching 100% in some cases. On the other hand, some of the evaluated zones were affected by grazing, which negatively strained vegetation development and soil quality (erosion) in the first steps of restoration.

3.2 Area evaluation

3.2.1. Landscape integration

Regarding chromatic and morphologic integration to the surrounding landscape, the majority of the evaluated restorations (93%) present good results. However, in some cases, the presence of artificial morphologies (cliffs in hilly landscapes, isolated tips, or repetitive and linear slope-berm morphology) and the dominance of herbaceous vegetation in a site surrounded by forests make this integration difficult (figure 3), at least in the first stages of restoration.

3.2.2. Ecological connectivity and fauna presence

The presence of steep slopes or abrupt topographic changes is common on the boundaries of the quarries and could act as an ecological barrier for some animal species. Moreover, in the vast majority of the restored areas, structures for attracting fauna (refuges, drinking troughs or woody plants with edible fruits) are missing. Nevertheless, in most of the evaluated areas diverse fauna traces (mainly wild boar and rabbit traces) were observed. Burrows were observed in approximately one third of the evaluated areas, and nests were only observed in one quarry.

3.2.3. Anthropic impacts

Approximately 1/3 of the areas were affected by anthropogenic impacts of various types. The most common effects were related to dumping, mainly in quarries located near to urban areas, and to the presence of abandoned infrastructures and machinery (i.e. ruins of buildings, sheds, conveyor belts or old bulldozers and dumpers) from the previous mining activity (Figure 4).

3.3 Indicators weight

As a result of the expert panel weighting process, a ranking of the indicators per group was made (Table 5). Zone indicators obtained greater weight than area indicators. Among the zone indicators, geotechnical risk was the most relevant since stability problems of the slopes compromise the success of the restoration. The presence of broken channels in the drainage network, directly related to geotechnical instabilities and erosion problems, was considered the second most important indicator. Geomorphologic integration was rated as the third due to its implications in geotechnical risks and soil degradation.

According to the criteria of the expert panel and the field observations, evaluation parameters with a weight higher than 2% were considered key indicators for ecological restoration success and must be taken into special consideration when analyzing the results of the evaluations.

3.4 Restoration Quality Index (RQI) calculation and assessment

Using the results of the quality indicators per zone and area, the whole RQI was calculated. Most of the restorations evaluated had a global RQI >70 since the relatively high number of parameters considered t make it difficult to have low RQI values. For this reason, a restoration with low values in a specific key indicator could obtain a relatively high global RQI value. In order to avoid that critical situations hidden by high RQI values and that could threaten the restoration, the adoption of corrective measures is recommended when:

- $RQ_x = 0$ for any indicator
- $RQ_x < 0.5$ for a key indicator

Usually, restorations with an RQI > 85 have an $RQ_x > 0$ on all key indicators. In these situations it could be considered a good result, meaning that the restoration objective has been achieved. However, the adoption of corrective measures could not be excluded in some cases or may be recommended in order to improve some aspects to better guarantee that the ecosystem transition towards a more mature and resilient state occurs. According to this, we could consider that mining companies can regain the restoration bond when they have obtained an RQI > 85 and an $RQ_x > 0$ for key indicators, and have adopted the recommended corrective measures. An example of the application of the RESTOQUARRY protocol is shown in Table 6. In this case, an RQI of 87 was achieved, but soil depth, woody species richness, chromatic and textural integration, woody plants with fruits, and grazing triggered warning alerts and improvement recommendations were needed. It can be seen that the use of this assessment procedure gives a detailed picture of the restoration status. The general overview of this example of evaluation can be that the restoration goals have been reached, although issues related to plant development should to be improved.

4. Discussion

The RESTOQUARRY protocol is a procedure that has been designed to help the evaluation of open mine restorations, using objective information obtained through simplified methodologies available for a non-specialized public. The protocol aims also to directly involve engineers of extractive companies in the design and monitoring process of the restoration of their mines, trying to respond to some demands from practitioners (Clewel & Rieger, 1997; Ockendon et al. 2018). Moreover, the RESTOQUARRY protocol provides a decision-making system useful for public administration bodies responsible for monitoring and evaluating mine restorations. This evaluation system is a very committed process, which must guarantee the correct evolution of the restorations towards the desired reference (eco)system, and which must maximize the provision of ecosystem services (Comín et al., 2018). In addition, this evaluation process must ensure that the return of the restoration bonds deposited by extractive companies is decided on an objective and quantifiable basis, and made in the correct time, not unnecessary extending the guarantee time, neither shortening it.

The vast majority of the indicators proposed in the protocol indirectly evaluate (proxies) ecosystem services and/or ecosystem functions, allowing the quantification of some of them. For example, erosion control, soil fertility, nutrient recycling or nutrient retention are evaluated through soil quality, soil erosion, and vegetation indicators. Even the most general indicators (area indicators), such as those related to anthropic impacts or landscape integration, could be considered proxies of ecosystem services linked to non-material benefits obtained through experiences (for example, cultural services).

The RESTOQUARRY protocol allows good quality restorations to be distinguished from those that need to take corrective measures (i.e. minor revision) and those that have critical failures that pose a risk to all the restoration efforts made (i.e. major revision). The simplicity of the protocol is not achieved at the expense of reliability or replicability since it is based on a wide literature review and the extensive knowledge of a panel of experts in the related fields (ecologists, quarry engineers, administration representatives). Moreover, this protocol has been tested in a wide representative sample of open-pit mines, with the direct participation of the end-users. One of the essential aspects of the protocol is that it does not evaluate the activities that have been carried out in the restoration, but rather its effective results. After applying the RESTOQUARRY protocol, we able to determine the whole restoration quality and to identify the critical features that need to be improved in the extractive activities assessed. Thereby most of the restorations evaluated in this work need the application of corrective measures in order to achieve the minimum standard quality. The RESTOQUARRY protocol also intends to be useful at the stage of restoration design, as it provides evaluation criteria that will be applied at the end of the restoration works. Engaging mine workers and engineers in the evaluation of restoration helps to improve the restoration works and their implication in the restoration process, which consequently could enhance the quality of the restorations carried out by these companies.

4.1 Similarities and differences with other evaluation procedures

Despite there being lots of studies evaluating ecological restorations (Ruiz-Jaen & Aide, 2005; Wortley et al. 2013), to our knowledge, there are not simplified methodologies readily available for practitioners, that give information about ecosystem services and assess the decision-making process. Landscape Function Analysis methodology (Tongway and Hindley, 2004) is a methodology that fits with these objectives; however it is impractical for a non-scientific public due to its complexity. Other studies also take a similar approach to RESTOQUARRY (Comín et al. 2018; Derhé et al. 2016; Lithgow et al. 2015; Bulloch et al. 2011; Birch et al. (2010)), taking into consideration the provision of ecosystem services and/or the ecosystem functions, but at a larger scale, with different target reference sites, and more focused on planning restorations than on evaluating the executed ones. While these other studies are focused on ecosystem services provided by ecological restoration in a general way (Comín et al. 2018; Bulloch et al. 2011; Birch et al. 2010), these works do not address the measure of some field parameters directly linked to the quantification of ecosystem services (i.e. carbon storage, nutrient cycling, water regulation, biomass production), as are made by RESTOQUARRY for evaluating restoration success. On the other hand, only a few studies are focused on the particular issue of the evaluation of mine restorations (Courtney et al. 2010; Dzwonko and Loster 2007), and they mainly assess very specific indicators related to soil rehabilitation or vegetation recover. Another differential characteristic of RESTOQUARRY is that includes zone specific indicators (geotechnical risk, drainage network, soil quality and degradation, vegetation structure and diversity) adapted to the specificities of mine restoration, such as the need of constructing a drainage network or creating a new soil layer (technosol).

4.2 Links between the current procedure of quarries control and the RESTOQUARRY protocol

Mine restoration evaluation tests should assure the correct restoration of mine sites and the recovery of the financial guarantees posted by mine companies conditioned to obtaining satisfactory results in these tests. This evaluation scheme is adopted in some countries like Canada (Mining Act), USA (Surface Mining Act), or the European Union (Directive 2006/21CE). In Spain, for example, the transposition of the EU Directive 2006/21/CE (RD 975/2009) established the need to monitor restorations works each year, until the end of the guarantee period. According to this law, the monitoring process could be done directly by competent administration officers or by accredited external companies. Currently, sincethe evaluation protocols, indicators, and reference values are not provided, the assessment result depends on the criteria of the evaluator, which sometimes varies according to its background. In this context, RESTOQUARRY protocol is a more accessible tool for a non-scientific public that could help to objectify and standardize the evaluation process, enhancing its transparency for administration bodies, companies, and citizens.

4.3 Methodological limitations

A limitation of the global RQI could be that it is confusing if it is not accompanied by an interpretation of the RQ_x partial values. The fact that a wide range of indicators is considered makes it difficult to obtain low RQI values despite the fact that some RQ_x could be very low or even 0, leading to relatively high global RQI values for restorations even though they may have critical faults. We propose the consideration of key indicators in order to decide the adoption of corrective measures could help to solve this problem. Other methodologies for evaluation (Lithgow et al. 2015) have used a similar approximation (hierarchical grouping) to prioritize among indicators, obtaining satisfactory results. However, by using the current criterion for key indicators definition (weight higher than 2%), more than a half of them are considered key indicators, which may be excessive. This criterion could be redefined in order to reduce the number of key indicators; however this will increase the chances that some poor quality restorations pass the assessment.

The RESTOQUARRY protocol has been designed and tested mainly in Mediterranean quarries, therefore its application in other climes or mine types could present mismatches in some indicators and reference values. Moreover, this protocol is not a suitable tool for evaluating very case-specific restorations, targeting singular habitats or species (endangered and/or protected) where an expert knowledge is needed. In these cases, some indicators and reference values included in the RESTOQUARRY could not be appropriate, or, alternative indicators should be evaluated. For the same reason, RESTOQUARRY may not be appropriate for evaluating agricultural restorations, but in these cases, the protocol could be easily adapted to specific goals by changing the set of indicators while preserving the general scheme.

Conclusions

The RESTOQUARRY protocol was designed to help mine companies, competent administration and accredited monitoring consultancies in the process of evaluating ecological restoration of mine sites. It consists of a multifactorial procedure, including selected expert-weighted indicators, that allows its large-scale application in the context of ecological restoration of Mediterranean quarries. The protocol could support mine companies in the decision-making process to select corrective measures for improving and optimizing the restoration process. At the same time, it could be useful for competent administration bodies to approve the return of restoration financial guarantees. In summary, RESTOQUARRY is a tool that can contribute to improve the practice and the monitoring of ecological restoration of mine sites.

Acknowledgements

This study was financed by the Catalan Government through the project "Research and Innovation in the process and control of extractive activities restoration". Authors thank the members of the expert panel: Esteve Serra (Generalitat de Catalunya), Montserrat Pedra (Generalitat de Catalunya), Jordi Cortina (Universitat d'Alacant), Albert Solé (Estación Experimental de Zonas Áridas-CSIC), Ramon Josa (Universitat Politècnica de Catalunya), David Badia (Universidad de Zaragoza), Montserrat Jorba (Universitat de Barcelona), Rosa Poch (Universitat de Lleida), Miquel Arán (Eurofins), Tomàs Carbó (Carbó Enginyers, SL), Juan Bautista Menéndez (Universitat Politècnica de Catalunya), Joan Pous (UNILAND), Fernando González (ARICEMEX), Xavier Foj, Manuel Juan (KNAUF) and Carles Ventura (PROMSA).

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TABLES

Table 1. Pre-selection of restoration quality zone indicators included in the preliminary proposal of evaluation protocol. Zones are described in this work as homogeneous portions of the whole restored area.

ZONE INDICATORS				
Geotechnical risk	**Erosion/physical degradation**	**Drainage network**	**Soil quality**	**Vegetation status and functionality**
Maximum diameter of fallen blocks (m) Area affected by fallen blocks (% of the total area) Area affected by landslides (% of the total area) Other signs of instability: cracks, subsidence, deformations, faults, fallen trees (qualitative)	Area affected by rill erosion (% related to the total area) Estimated rill erosion rates (Mg ha^{-1} $year^{-1}$) Rain splash protection (% of the surface protected) Surface crusts presence (qualitative) Sheet erosion (qualitative) Piping or subsurface flows (qualitative)	Drainage channels broken (% of total channels) Drainage channels filling-in (% of total channels) Drainage network functionality (% of damaged, stabilized and non-functional channels)	Soil depth (m) Particles <2 mm (g kg^{-1}) Clay content (g kg^{-1}) Organic matter (g kg^{-1}) Carbonates (g kg^{-1}) Electrical conductivity, 1:5 extract (dS m^{-1}) Soil pH Total nitrogen (%) Available phosphorous (mg kg^{-1}) Available potassium (mg kg^{-1}) Physical contaminants presence (number of elements observed)	Plant cover (%) divided into: herbaceous cover and woody species (shrubs and trees) cover Area occupied by exotic/invasive species (% of the total area) Species with fruits (number of species) Mortality of planted woody species (%) Woody species richness (% related to richness on reference site) Woody species density (% related to density in reference site, per species) Woody species recruited (number) Herbaceous species richness (% related to richness on reference site)

Table 2. Pre-selection of restoration quality area indicators included in the preliminary proposal of evaluation protocol.

AREA INDICATORS		
Landscape integration	**Ecological connectivity and fauna presence**	**Anthropic impacts**
Chromatic and textural integration (qualitative) Geomorphic integration (qualitative) Internal road networks (functionality, density and width)	Ecological barriers (presence and type) Woody plants with edible fruits (Species and density) Fauna refuges/supply structures (presence) Fauna observations (number and species) Fauna paths (presence) Fauna traces (presence) Nests (presence) Burrows (presence)	Uncontrolled vehicle circulation (qualitative) Waste dumping (type, magnitude and distribution) Grazing (presence and intensity) Abandoned constructions and facilities (presence, magnitude and height)

Table 3. Geological substrates and ranges of precipitation and air temperature in a representative selection of the extractive activities included in the pilot test (n=55).

Dominant lithology (n=number of activities included)	**Dominant mineralogy**	**Precipitation rank (mm/year)**	**Mean annual air temperature rank (ºC)**
Limestone (24)	Carbonatic	526-747	14.1-16.1
Gravel (9)	Mixed	416-799	13.1-15.2
Lignite (6)	Carbonatic	408-888	10.6-15.8
Sand and clay (6)	Siliceous and carbonatic	506-795	14.8-15.6
Evaporites (4)	Gypsic, saline and carbonatic	585-793	13.2-14.6
Basalt (2)	Siliceous	685-745	15.8-16.2
Weathered granite (2)	Siliceous	653-753	15.1-16.3
Granite (2)	Siliceous	599-613	13.8-15.3

Table 4. Results for substrate quality indicators on the evaluated zones. *Data refer to <2mm soil fraction.

	Soil depth (m)	**Particles <2 mm (%)**	**Clay content (%)***	**EC, 1:5 extract (dS m^{-1})***	**pH***
Average	22	44	24	0.4	8.0
Max.	50	94	50	2.2	8.8
Min.	0	19	6	0.1	6.5
Median	20	42	23	0.2	8.0
Standard deviation	22	19	10	0.5	0.3
	Carbonates (%)*	**Organic matter (%)***	**Total N (%)***	**Available P (mg kg^{-1})***	**Available K (mg kg^{-1})***
Average	22	2.6	0.14	33	217
Max.	58	12.4	0.57	199	972
Min.	0	0.2	0.02	2	38
Median	23	1.9	0.10	19	148
Standard deviation	15	2.2	0.11	42	184

Table 5. Weight of the selected indicators according to their importance for restoration success measurement after pairwise comparison by experts panel members. *key indicators.

GROUP	GROUP WEIGHT (%)	INDICATOR	INDICATOR WEIGHT (%)
Geotechnical risk	18.0	Area affected by landslides*	9.9
		Area affected by fallen blocks*	4.7
		Other signs of instability*	3.4
Erosion and physical degradation	15.3	Rain splash protection*	4.5
		Area affected by concentrate erosion*	4.3
		Estimated erosion rates*	3.7
		Other degradation processes*	2.8
Drainage network	15.0	Drainage channels broken*	7.7
		Drainage channels filling*	3.9
		Drainage network functionality*	3.4
Soil quality	14.3	Soil depth*	2.4
		Particles <2 mm content*	2.5
		Texture	1.9
		Organic matter / Nitrogen*	2.4
		Electrical conductivity, 1:5 extract	2.0
		pH / Phosphorous / Potassium	2.0
		Impurities (glass, plastics, metals, etc.)	1.1
Vegetation status and functionality	12.7	Plant cover*	2.9
		Woody species richness*	2.6
		Woody species density	2.0
		Woody species recruitment	1.7
		Area occupied by exotic/invasive species	1.7
		Herbaceous species richness	1.8
Landscape integration	12.0	Chromatic and textural integration*	3.1
		Geomorphologic integration*	7,2
		Road network	1.7
Ecological connectivity and fauna presence	6.4	Ecological barriers*	2.1
		Woody plants with edible fruits	1.3
		Fauna refuges/supply structures	1.1
		Fauna observations	1.9
Anthropic impacts	6.3	Uncontrolled vehicle circulation	1.6
		Waste dumping*	2.4
		Grazing	1.0
		Abandoned constructions and facilities	1.3

Table 6. Example of RQI index calculation for a quarry evaluated using the RESTOQUARRY protocol. Critical indicators warning: $RQ_x < 0,5$ for key indicators (weight more than 2%) or $RQ_x = 0$ for any indicator.

GROUP	INDICATOR	RQ_x	RQI_x	CRITICAL INDICATORS
Geotechnical risk	Area affected by landslides	1.0	9.9	
	Area affected by fallen blocks	1.0	4.7	
	Other signs of instability	1.0	3.4	
Erosion and physical degradation	Rain splash protection	1.0	4.5	
	Area affected by rill erosion	1.0	4.3	
	Estimated erosion rates	1.0	3.7	
	Other degradation processes	0.9	2.5	
Drainage network	Drainage channels broken	1.0	7.7	
	Drainage channels filling	1.0	3.9	
	Drainage network functionality	1.0	3.4	
Soil quality	Soil depth	0.2	0.5	WARNING
	Particles <2 mm content	1.0	2.5	
	Texture	1.0	1.9	
	Organic matter / Nitrogen	0.6	1.5	
	Electrical conductivity, 1:5 extract	1.0	2.0	
	pH / Phosphorous / Potassium	0.2	0.3	
	Physical pollutants	0.9	1.0	
Vegetation status and functionality	Plant cover	1.0	2.9	
	Woody species richness	0.2	0.5	WARNING
	Woody species density	0.9	1.9	
	Woody species recruitment	1.0	1.8	
	Area occupied by exotic/invasive species	1.0	1.7	
	Herbaceous species richness	1.0	1.7	
Landscape integration	Chromatic and textural integration	0.3	0.8	WARNING
	Geomorphologic integration	1.0	7.2	
	Road network	1.0	1.7	
Ecological connectivity and fauna presence	Ecological barriers	1.0	2.1	
	Woody plants with fruits	0.0	0.0	WARNING
	Fauna refuges/supply structures	1.0	1.1	
	Fauna observations	1.0	1.9	
Anthropic impacts	Uncontrolled vehicle circulation	1.0	1.6	
	Waste dumping	0.5	1.3	
	Grazing	0.0	0.0	WARNING
	Abandoned constructions and facilities	1.0	1.3	
		RQI = 87		Recommendation: bond return dependent on adoption of corrective measures

Table 1. Pre-selection of restoration quality zone indicators included in the preliminary proposal of evaluation protocol. Zones are described in this work as homogeneous portions of the whole restored area.

ZONE INDICATORS				
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Table 2

AREA INDICATORS		
Landscape integration	**Ecological connectivity and fauna presence**	**Anthropic impacts**
Chromatic and textural integration (qualitative) Geomorphic integration (qualitative) Internal road networks (functionality, density and width)	Ecological barriers (presence and type) Woody plants with edible fruits (Species and density) Fauna refuges/supply structures (presence) Fauna observations (number and species) Fauna paths (presence) Fauna traces (presence) Nests (presence) Burrows (presence)	Uncontrolled vehicle circulation (qualitative) Waste dumping (type, magnitude and distribution) Grazing (presence and intensity) Abandoned constructions and facilities (presence, magnitude and height)

Table 3

Dominant lithology (n=number of activities included)	**Dominant mineralogy**	**Precipitation rank (mm/year)**	**Mean annual air temperature rank (ºC)**
Limestone (24)	Carbonatic	526-747	14.1-16.1
Gravel (9)	Mixed	416-799	13.1-15.2
Lignite (6)	Carbonatic	408-888	10.6-15.8
Sand and clay (6)	Siliceous and carbonatic	506-795	14.8-15.6
Evaporites (4)	Gypsic, saline and carbonatic	585-793	13.2-14.6
Basalt (2)	Siliceous	685-745	15.8-16.2
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Table 4

	Soil depth (m)	**Particles <2 mm (%)**	**Clay content (%)***	**EC, 1:5 extract (dS m^{-1})***	**pH***
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Median	20	42	23	0.2	8.0
Standard deviation	22	19	10	0.5	0.3
	Carbonates (%)*	**Organic matter (%)***	**Total N (%)***	**Available P (mg kg^{-1})***	**Available K (mg kg^{-1})***
Average	22	2.6	0.14	33	217
Max.	58	12.4	0.57	199	972
Min.	0	0.2	0.02	2	38
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Table 5

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		Area affected by concentrate erosion*	4.3
		Estimated erosion rates*	3.7
		Other degradation processes*	2.8
Drainage network	15.0	Drainage channels broken*	7.7
		Drainage channels filling*	3.9
		Drainage network functionality*	3.4
Soil quality	14.3	Soil depth*	2.4
		Particles <2 mm content*	2.5
		Texture	1.9
		Organic matter / Nitrogen*	2.4
		Electrical conductivity, 1:5 extract	2.0
		pH / Phosphorous / Potassium	2.0
		Impurities (glass, plastics, metals, etc.)	1.1
Vegetation status and functionality	12.7	Plant cover*	2.9
		Woody species richness*	2.6
		Woody species density	2.0
		Woody species recruitment	1.7
		Area occupied by exotic/invasive species	1.7
		Herbaceous species richness	1.8
Landscape integration	12.0	Chromatic and textural integration*	3.1
		Geomorphologic integration*	7,2
		Road network	1.7
Ecological connectivity and fauna presence	6.4	Ecological barriers*	2.1
		Woody plants with edible fruits	1.3
		Fauna refuges/supply structures	1.1
		Fauna observations	1.9
Anthropic impacts	6.3	Uncontrolled vehicle circulation	1.6
		Waste dumping*	2.4
		Grazing	1.0
		Abandoned constructions and facilities	1.3

Table 6

GROUP	INDICATOR	RQ_x	RQI_x	CRITICAL INDICATORS
Geotechnical risk	Area affected by landslides	1.0	9.9	
	Area affected by fallen blocks	1.0	4.7	
	Other signs of instability	1.0	3.4	
Erosion and physical degradation	Rain splash protection	1.0	4.5	
	Area affected by rill erosion	1.0	4.3	
	Estimated erosion rates	1.0	3.7	
	Other degradation processes	0.9	2.5	
Drainage network	Drainage channels broken	1.0	7.7	
	Drainage channels filling	1.0	3.9	
	Drainage network functionality	1.0	3.4	
Soil quality	Soil depth	0.2	0.5	WARNING
	Particles <2 mm content	1.0	2.5	
	Texture	1.0	1.9	
	Organic matter / Nitrogen	0.6	1.5	
	Electrical conductivity, 1:5 extract	1.0	2.0	
	pH / Phosphorous / Potassium	0.2	0.3	
	Physical pollutants	0.9	1.0	
Vegetation status and functionality	Plant cover	1.0	2.9	
	Woody species richness	0.2	0.5	WARNING
	Woody species density	0.9	1.9	
	Woody species recruitment	1.0	1.8	
	Area occupied by exotic/invasive species	1.0	1.7	
	Herbaceous species richness	1.0	1.7	
Landscape integration	Chromatic and textural integration	0.3	0.8	WARNING
	Geomorphologic integration	1.0	7.2	
	Road network	1.0	1.7	
Ecological connectivity and fauna presence	Ecological barriers	1.0	2.1	
	Woody plants with fruits	0.0	0.0	WARNING
	Fauna refuges/supply structures	1.0	1.1	
	Fauna observations	1.0	1.9	
Anthropic impacts	Uncontrolled vehicle circulation	1.0	1.6	
	Waste dumping	0.5	1.3	
	Grazing	0.0	0.0	WARNING
	Abandoned constructions and facilities	1.0	1.3	
		RQI = 87		Recommendation: bond return dependent on adoption of corrective measures

FIGURES

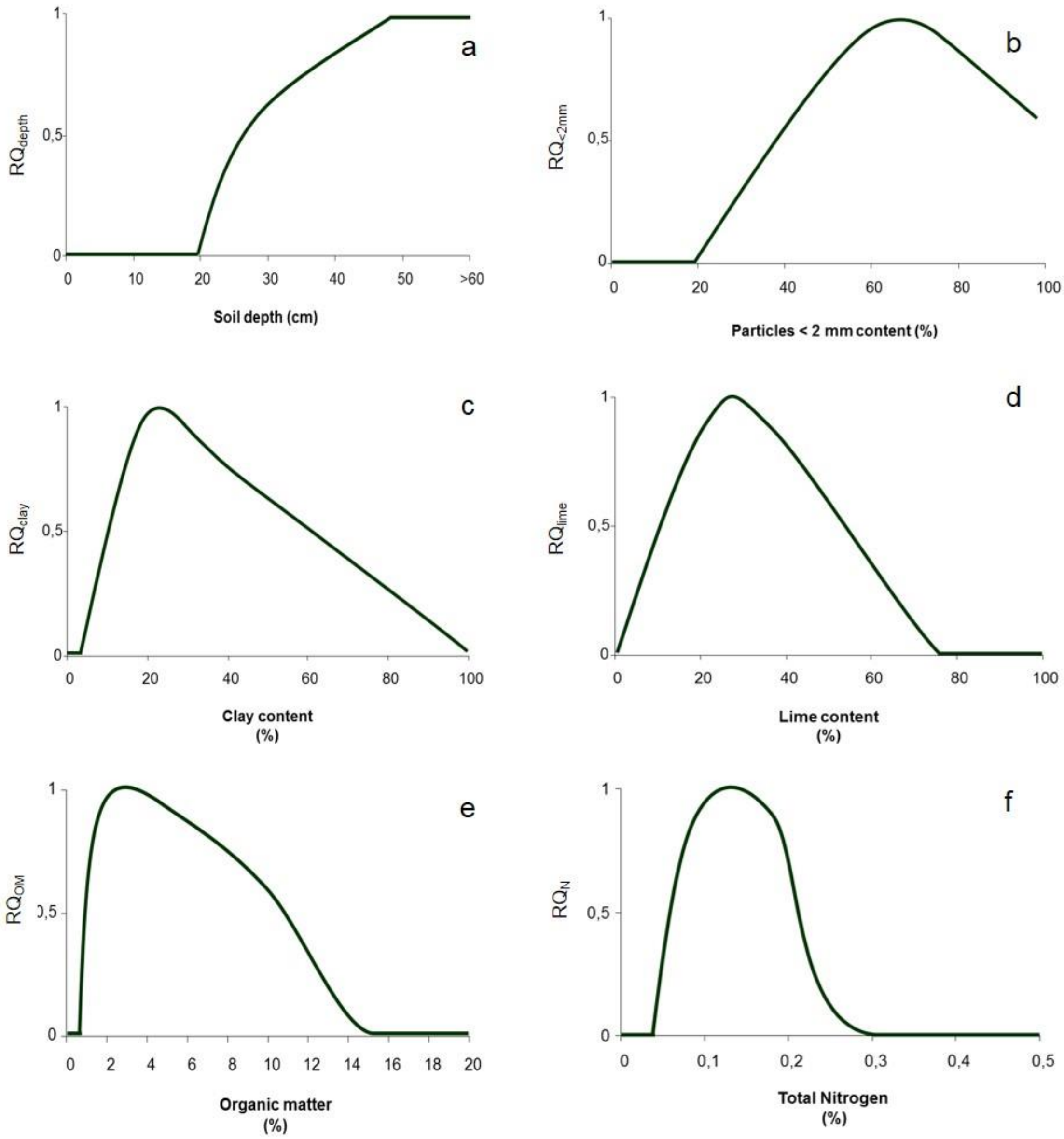

Figure 1. Functional curves for some soil parameters: (a) soil depth, (b) particles < 2 mm, (c) clay content, (d) lime content, (e) organic matter, (f) total nitrogen. RQ_x= restoration quality value for the respective parameter.

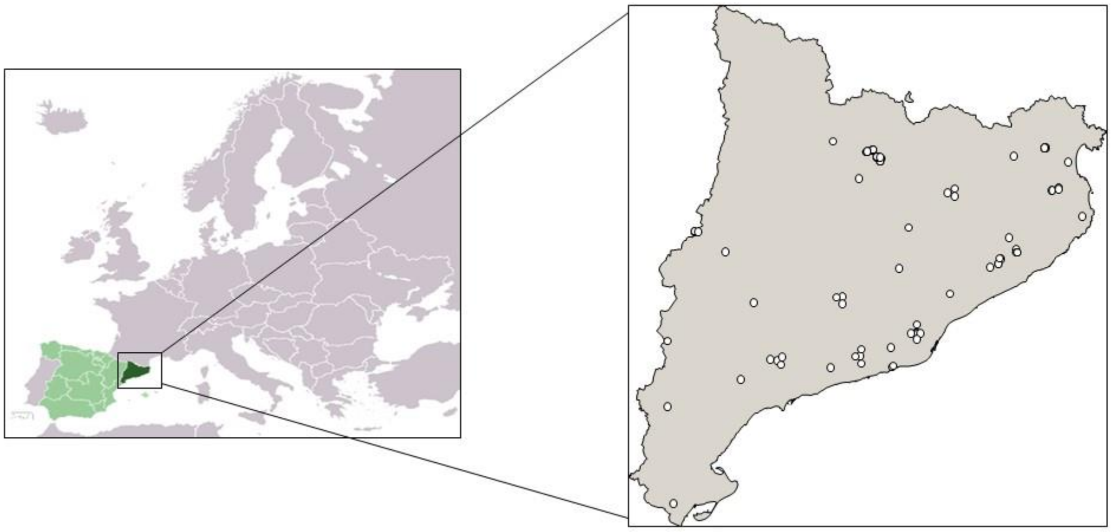

Figure 2. Geographical distribution of restored mining activities evaluated applying the RESTOQUARRY methodology, in the NE Iberian Peninsula.

Figure 3. Differences in vegetation type between restored zones and surrounding areas (left), and the presence of artificial morphologies, like walls (cliffs) in flat/hilly landscapes (right), that make the integration of the restored areas to the landscape difficult.

660

661

Figure 4. The presence of abandoned buildings and machinery of the former extractive activity has a negative impact on the integration of the restored areas and represents a risk for people.