Evaluation of restoration of an asbestos mine, in northern Greece, eight years after restoration works

Petros Ganatsas*, Marianthi Tsakaldimi, Lazaros Ioannidis, Theologia Strafkou

Department of Forestry and Natural Environment, Aristotle University of Thessaloniki, Thessaloniki, Greece

*corresponding author: pgana@for.auth.gr

Abstract

This paper deals with the evaluation of rehabilitation of spoils depositions of asbestos mine MABE, Kozani, in northern Greece, eight years after restoration works. In order to succeed in this, we monitored all the restoration actions during the period of restoration works, as well as during the post-restoration period of eight years after the end of restoration works. The evaluation showed that the mining area subjected to restoration is now characterized, eight years after restoration, by high land stabilization, satisfactory woody vegetation cover, low erosion risk, low concentration of asbestos fibres in the air and water, and furthermore it was aesthetically integrated into the surrounding landscape. Even though the great difficulties due to the huge pile of spoils depositions that had been created during mining, the selection of the specific restoration actions greatly contributed to the achievement of a sustainable post-mining environment. The suitable land transformation and the satisfactory establishment of forest vegetation created a safe from asbestos fibres environment and for sustainable future land use of the previous mine area as forest, which in many cases is the most appropriate post-mining use for contaminated mining areas.

Keywords:
land disturbance
mine rehabilitation
plantings
slope stabilization
spoils depositions

Introduction

Minerals have been for a long time great economic resources worldwide. Their extraction from the earth usually causes strong land injuries and serious environmental problems, especially in the case of surface mining. During the last decades, the care of the environmental impacts and mine rehabilitation have been greatly arising worldwide. Accordingly, a common environmental policy approach has been adapted both from financial and environmental point of view. The restoration of a disturbed mined land can be considered as ecosystem reconstruction that requires a wide ecological background. However, for many cases, the scarce data on post-restoration monitoring and research has resulted in low possibilities to improve the theory and practice of ecological restoration in a mining operation (Cooke and Johnson, 2002).

The research on mine land reclamation and its ecological restoration involves many research fields, such as mining, geology, geography, land use, environment, landscape, ecosystem, agriculture and forestry, biology, soil science, and social economy etc. and the amount of information is huge. Therefore, reasonable organization and management of research data are needed (Huading et al., 2005). An important problem faced in the procedure of mine areas rehabilitation is the choice of future land use (Cairney, 1995) and the sustainable use of the mining area. Forestry is considered a common land use of abandoned mine areas in many cases. However, for an effective forest establishment in such areas, some great problems must be addressed, named: land
transformation and stabilization, formation of low-inclination slopes, the finding of the necessary quantities of good quality topsoil to cover the spoils, the selection of the suitable plant species capable of surviving in such extreme site conditions, any possible problems about toxicity end environmental pollution, and finally an effective well-organized, and adequate financially supporting, planning of rehabilitation (Ganatsas, 2020). From ecological and environmental perspectives, revegetation of disturbed mine areas is commonly used mainly in order to succeed in erosion control and helping in site stabilization. Additionally, vegetation establishment encourages the development of mine soil, improves the landscape aesthetics and increase ecosystem productivity (Skousen and Zipper, 2010), resulting in an increase in the sustainability of mining operations (Gastauer et al., 2018). An important point to succeed in all the above goals is the speed of plant canopy closure which should be quite high in order to effectively control erosion and land stabilization.

Despite the urgent demand for sustainable mining, the revegetation and rehabilitation of areas degraded by mining remain challenging, mainly due to high uncertainties about species selection, planted species survival and growth, and management and control of alien invasive species (Gastauer et al., 2018). The selection of plant species in mine rehabilitation is based on several approaches; the followings are the most adapted: i) the use of fast-growing plant species for a quick canopy closure and effective erosion control, ii) the use of native species in order to conserve local biodiversity, and help in the landscape integration of the mine area to the wide area, within the mine is laying. However, due to the usually adverse environmental constraints of the degraded mine sites, all the selected revegetation activities, including plant species selection, must be adapted to the specific environmental conditions. iii) the use of plant species capable of developing symbioses with mycorrhizal fungi and rhizobia in order to increase soil biological activities (Anderson, 2008; Sprent, 2009), iv) includes some plant species characterized as attractors of pollinators that are necessary to establish multi-trophic networks, and achieve dynamic, process-based restoration goals (Perring et al., 2015) v) the revegetation and the target plant communities should be compatible with the desired post-mining land-use and restoration targets (Ganatsas, 2020). Finally, social and economic parameters at local and regional scale form the framework for the sustainability of land use and mining operations.

In the cases where mining results in environmental pollution, such as asbestos mining, that causes great contamination problems, the mine restoration is urgent due to the high hazards of asbestos to human, since exposure to asbestos dust increases the risk of lung cancer, while it may also cause mesothelioma and nonmalignant lesions in the pleura (Szeszenia-Dabrowska et al., 2012; Cornelissen et al., 2019). Thus, ecological restoration of asbestos mines differs from other mining restoration projects due to the human health-risk challenges, which in turn, necessitates taking special precautions during such projects (Lévesque et al., 2020). Mining of asbestos has stopped in Greece since 2000 as in many counties in the world, following the EU relevant regulations, while asbestos is still mined in Russia, China, Brazil and Kazakhstan (Cornelissen et al., 2019).

An inactive Asbestos Mine, known as MABE, is located in northern Greece at the Zidani region of the Kozani Prefecture (Koumantakis et al., 2009). The operation of the mine started in 1982 and ended in February 2000, causing serious environmental problems from mining, and especially, due to the spoils depositions that formed a huge pile of the unused soil materials (Tsatsanifos et al., 2006; Gidarakos et al., 2008; Zagas et al., 2010). This created the most serious and dangerous for life problem since the created depositions pile of 180 m height, and the high slope inclination was being allowed in the exposition to wind and water erosion of the dangerous asbestos fibers. Therefore, the mine and the deposits urgently required remediation works, such as removal of large contaminated objects from the mine buildings and revegetation of the deposit areas, in order to reduce the asbestos levels in the air and in the river water (Koumantakis et al., 2009). This is in accordance with the overall goal of rehabilitation on asbestos mines worldwide, which is to permanently eliminate the dispersion of asbestos fibres and return the disturbed area to an ecologically stable state (Cornelissen et al., 2019).

The aim of the current study was the evaluation of rehabilitation and ecological restoration of an asbestos mine eight years after restoration works. Specifically, the study concerns the evaluation of the rehabilitation of spoils deposition of asbestos mine MABE, Kozani, in northern Greece, that was carried out in order to achieve stability of the vulnerable tailings slopes of spoils deposition, to prevent the dangerous asbestos fibers transport in the atmosphere, and to minimize dispersion of asbestos fibers by surface water or groundwater. Relevant studies before restoration had indicated that the mine and the depositions constitute major sources of pollution for the broader area, while the risk of an occurrence at local or regional landslide was high (Anastasiadou and Gidarakos, 2007), especially due to the depositions pile.

Materials and Methods

Study area

The study concerns the mining area of the abandoned asbestos mine MABE in Kozani area, northern Greece. The area is laying in SW part of Kozani Prefecture, and it is located close to (1 km far away) the longest Greek river ‘Aliakmon’ and the artificial lake of Polyphyo. The water of the river is used to supply the citizens of
Thessaloniki. The mining area lays on a hilly-mountainous area, in elevation ranging from 400 to 700 m. The wide area is characterized by a dense network of streams, while the topography consists of a set of slopes of medium inclination. Geologically the area is located to the western border of the Pelagonic Zone, which is consisting of crystalline schist substrate (gneiss, schist, amphibolites, granites, ophiolite rocks) (Rassios, 2008). Bioclimatically, the area, according to the Emberger diagram (Mavromatis, 1981), is meso-mediterranean, sub-humid with harsh winters. According to the nearest Meteorological station of Kozani, the mean annual rainfall is 563 mm, and the mean temperature is 13.3°C. The vegetation of the area belongs to Quercetalia pubescentis floristic zone (Athanasiadis, 1986). The landscape of the wider area is composed of a combination of hilly relief, a dense network of small streams that enter to Aliakmon river, and the artificial lake of Polyphyto. The main areas of the asbestos mine consist of the excavation area with a small lake that formed in the basis of the front of the industrial infrastructure, and a hill of spoils deposition. The mine covers a total area of 414 ha, which consisted of the quarry mining area, the small artificial lake created by mining, the area of spoils deposition, the plant area, and the rest area (Figure 1). During the mine operation, no care was given to protect the environment, and even worse no any treatment applied for spoils deposition that had been continuously put untreated in the deposition area. The mine depositions had formed an artificial hilly area resulting in a huge pile of unused land materials. The bank’s height was over 180 m with very steep slopes, and due to the high inclination and the loose structure of the spoils, many serious landslides phenomena have been occurred (Tsatsanifos et al., 2006; Zagas et al., 2010). This created the most serious and dangerous for life problem since the created pile of 180 m height was being allowed in the exposition to wind and water erosion of the dangerous asbestos fibers (Figure 2).

Concerning the topography details and the formation of spoils depositions slope, in the north-eastern exposures, the slope inclination was very steep 80-90%, and the depositions mainly consisted of materials with the particle size of sand gravel and sludge-clay gravel. In the southeastern exposures, slope inclination was a little lower, 70-90%, and the depositions consisted mainly of asbestos spoils with coarse structure. As it is seen in the pictures, no signs of life colonization in these materials has been occurred, even though many years have been passed. Within this time period, no any plant or animal species managed to recruit the spoils area, concluding that these materials are of high toxicity for all type of organisms. This shows the emergency for restoration actions in order to stop any asbestos fibers dispersal through wind and water. Additionally, based on the data monitoring of the concentration values of dangerous asbestos fibers in the air and water in several points in the area, it was observed high concentration values over the

Figure 1. The mining area of MABE asbestos mine, in northern Greece before restoration, in 2007, showing the quarry area with the small artificial lake, the depositions area, the Mine Plant and the rest mining area.

Figure 2. The spoils depositions of MABE asbestos mine, in northern Greece, before restoration, in 2007.
Methods

The main target of the land reclamation and ecological restoration project was focused on the spoils deposition of the asbestos mine. Thus, we studied analytically the results of the restoration project on topography and spoils deposition’s slope, vegetation and landscape of the study area. A set of indicators was used for restoration evaluation success, based mainly on the standards set by the Surface Mining Control and Reclamation Act (SMCRA), which is the primary federal law that regulates the environmental effects of coal mining in the United States (Rodrique et al., 2002; Zipper et al., 2011; Adams, 2017; Sena et al., 2018; Dement et al., 2020). The Chapter 7, Standards and Methods for Evaluating the Success of Reclamation, of this law, define in the list of Table 7-1, the most important of performance standards for reclamation that SMCRA requires. These are:

- restoration of the land’s approximate original contour (AOC);
- stabilization of the surface against erosion;
- salvage and protection of topsoil, with special requirements for prime farmlands;
- minimization of disturbance to the hydrologic balance, including maintenance of water quality;
- restoration of the essential hydrologic functions of alluvial valley floors (AVFS),
- and restoration of aquifer recharge capacity; protecting revegetation and post-mining water quality from acid-, alkaline- and toxic forming overburden;
- establishment of a diverse, effective, and permanent vegetative cover of the same seasonal variety native to the area and capable of plant succession and regeneration;
- and assumption of responsibility for successful revegetation for a period of 10 years after completion of work on the area.

Between those, the following indicators were used, as most appropriate under the specific conditions of MABE asbestos mine:

- The degree of slope stabilization success
- The degree of protecting soils from erosion
- The degree of successful land transformation to the previous stage (before mining)
- The degree of vegetation establishment and plant canopy closure.
- The concentration of asbestos fibers in air and water in several points of the mining area.
- The degree of aesthetic integration of the disturbed mining area to the surroundings.

According to the restoration project (ANKO, 2004), emphasis was given to stabilize the depositions, to minimize slope inclination, to build soil organic matter by adding topsoil, and to establish woody vegetation. All these are considered essential for a successive ecological restoration because they contribute and accelerate the natural recovery process (Singh et al., 2002). Based on the restoration plan, the reduction of the slope inclination of the depositions pile would be achieved through the formation of terraces (bench plains) of different width, based on the most effective and economical solution (Tsatsanifos et al., 2006; Zagas et al., 2010). The restoration works started in 2010 and ended in 2012.

For the research purposes, a series of images, free available by Google Earth Pro, before, during, and after restoration works were collected and studied during the period 2007-2020. The performed restoration works and land transformation data were analyzed, included area affected, slope inclination changes, vegetation cover, eroded area. The degree of slope stability was estimated as the risk for landslides,

permissible exposure limit (PEL) determined for asbestos in Europe (0.01 fibres/cm³ or 1/cm³) (Anastasiadou and Gidarastos, 2007). The measurements made in the area after mining stop and before restoration (in the years 2004-2005) showed that the values of asbestos fibre concentrations in the atmospheric air were above the permissible limit of Directive 2003/18/EU, and the calculated cancer risk was exceptionally high (Anastasiadou and Gidarastos, 2007). Furthermore, there was a high risk of landslides due to the low stability of the depositions tailings. The first instability phenomena on the depositions pile were observed in 1987 in the form of flexural-shear fractures on the surface of the deposits. The maximum daily displacements of the slopes were on the order of 8-21 cm per day, while the average weekly were on the order of 1.5 m per week. The displacements of the bedrock were on the order of 4-14 cm per day, with an average 65 cm per week (Tsatsanifos et al., 2006).

After ten years of mine abandonment with no any human and life protection measures, an important restoration project was carried out focused mainly on the restoration of the most dangerous spoils depositions, aiming at life protection (Zagas et al., 2010). The overall goal of the approved restoration project was to achieve stability of the tailings slopes, to prevent asbestos fibers transport in the atmosphere, and to minimize dispersion of asbestos fibers by surface water or groundwater (Tsatsanifos et al., 2006). The project included an analytical plan of land transformation and stabilization, covering the dangerous spoils with soil material, establishment of appropriate vegetation, and improvement of the landscape aesthetics. The overall goal was to restore the mining area, to protect the human as well as the environment of the general area, by reforming the area of mining, stabilization of spoils and prohibiting any further asbestos fibers dispersal through wind and water. This study aims at the evaluation of the mine rehabilitation, and ecological restoration works carried out. In order to succeed this, we monitored all the restoration actions during the period of restoration works, as well as during the post-restoration period of eight years after the end of restoration works.
categorized in five classes (Very high = 5, High = 4, Medium = 3, Low = 2, Zero = 1). The determination of the areas with erosion problems, as eroded area in ha and percentage of the total restored area, in terms of rill density (m/m²), we considered the linear rill length (m) per surface area (m²/m²) (Morgan, 1995; Moreno-de las Heras, 2009). This was determined in each year of the eight-year monitoring program (2012, 2014, 2018 and 2020). We characterized eroded area as those areas with a linear rill length (m) per surface area >0.2 m².

The estimation of the degree of land transformation from the previous stage (before mining) was based on the approach of "approximate original contour" suggested by SMCRA. Common approaches to estimate land transformation are by trying to arbitrarily resemble the pre-mined topography or to imitate the surrounding terrain of the mined lands. We considered these pre-mine topographical conditions to compare the current conditions as a viable alternative. The natural landform with natural contouring was produced, and we compared the post-restoration topography in terms of differences on slope gradient. Especially, we computed the area for each slope inclination category, based on the created digital elevation model (DEM), and using the following classification for slope inclination on landslide (Çellek, 2020): Flat areas (slope angle less than 1°) = class 1, slopes of low inclination (angle 1°-15°) = class 2, slopes of medium inclination (angle 15°-30°) = class 3, and slopes of high inclination (angle >30°) class 4. Then, the differences were estimated and based on these differences; we additionally estimated the degree of land transformation using the following formula (equation 1):

$$DLD = \frac{100 \times (\sum SI_{i}^{aafter} - \sum SI_{i}^{abefore})}{\sum SI_{i}^{abefore}} \quad \text{equation (1)}$$

where $DLD$ is the Degree of Land Transformation (%) from the pre-mining conditions, $SI_{i}$ is the class of slope inclination of $i$ category, and $a$, the area belongs to this slope category, before mining (before) and after restoration (after).

Estimation of vegetation establishment and canopy closure was carried out by recording the performance of woody species planted in the deposition area. A number of sampling plots were taken in the restored area, eight years after planting, in summer 2020. These were focused on the main woody species planted in the area of deposition, which were: Robinia pseudoacacia, Pinus brutia, Cupressus sempervirens, Cupressus arizonica, and Quercus pubescens. Thirty sampling plots were taken of a size of 100 m² (10 x 10 m). Within the plots, all the planted tree individuals were measured for their height and diameter at breast height. Also, a visual estimation of canopy cover (closure) was assessed. The survival rate of the planted species was based on the number of trees recorded and the initial planting spacing. In order to estimate the impacts of restoration works on pollution limitation, the concentration of asbestos fibers was monitored in the area. Monitoring concerned the concentration of asbestos fibers in the air (f/cm³) in the depositions area, as well as in water (fibers*10⁶/l) in the small artificial lake created by mining in the front of the quarry (see Figure 1). All the available data collected and analyzed for the period before, during and after restoration (period 2007-2020). The recorded values were compared to the value 0.01 fibers per cubic centimeter (>0.01 f/cm³), as this value is the permissible exposure limit (PEL) determined for asbestos in Europe (Anastasiadou and Gidarakis 2007). The concentration in water was compared with the standard values set by EPA ($7 \times 10^6$ f/l) (Koumantakis et al., 2009).

Evaluation of the effect of restoration on the landscape aesthetics of the area and the modifications of the parameters that affected the visual absorptive capacity of the landscape were based on the changes of landscape visual absorption capacity. The visual absorption capacity of the landscape (VAC) is defined as the capacity of the landscape to absorb development actions without its character being significantly changed or its scenic quality reduced (Amir and Gidalizon, 1990; Lucas, 1991; BCMoF, 1995). VAC was estimated at the time before starting the restoration, in 2007, and eight years after ending the restoration works, in 2020. The evaluation was carried out using the following equation (2):

$$VAC = SI \times (SE + VRD + SCC + LD) \quad \text{equation (2)}$$

where: $SI$ = slope inclination, in a five-level classification, $SE$ = Soil Erosion, in a three-level classification, $VRD$ = Vegetation Regeneration Dynamics, in a three-level classification, $SCC$ = Soil Color contrast, in a three-level classification, and $LD$ = Landscape Diversity in a three-level classification (Anderson et al., 1979; Yeomans, 1979).

**Results**

Figures 3, 4, 5, 6 and 7 show the restoration progress of the mine area through the period of eight years after restoration works. In the first figure (Figure 3a), the mine area is shown in 2007, focused on the huge mass of spoils depositions before any restoration works. The height of depositions was 180 m. The land was extremely toxic since no any organism (plant or animal species) appeared even though the 10 years period of mine abandoned in 2000. This shows the great importance and the urgency for mine restoration. In the consecutive images, we see the restoration works, including firstly, the technical works concerning land transformation and stabilization (Figure 3b), according to geotechnical study, followed by phytotechnical works, including the formation of small terraces, plantings, seeding, establishment of irrigation system, and all the necessary additional works, that ended in
However, with this increase of medium inclination (91.6%), compared to 47.3% occupied before mining. occupying the great percentage of the restored area. The slopes of medium inclination (angle 15-30°), values less than 27°, a limit that was considered the upper limit for slope stabilization in the area (Tsatsanifos et al., 2006). However, a small part of the restored area of the spoils depositions presents erosion problems in terms of rill density (m/m²) (Moreno-de las Heras, 2009) (linear rill length (m) per surface area >0.2 m/m²), as it is seen in the low part in the series of the images. The eroded area ranges from 0.46 ha (0.62% of the restored area) in 2012 to 1.63 ha in 2018 (2.20%), and finally to 1.42 ha in 2020 (Table 1). This small area concerns the most sensitive part of the depositions since it lays in the point over the huge mass of spoils, of a height over 180 m (Figure 8).

Table 1. Monitoring of the restoration success, using a set of indicators, during eight years after the end of restoration works.

| Indicator                                             | Before restoration | At the end of restoration works | Two years after restoration | Six years after restoration | Eight years after restoration |
|-------------------------------------------------------|--------------------|---------------------------------|-----------------------------|----------------------------|-------------------------------|
| Degree of slope stability - Risk for landslides.      | 5                  | 2                               | 2                           | 2                          | 2                             |
| Eroded area, in ha (Rill density (m/m²))              | -                  | 0.46                            | 1.33                        | 1.63                       | 1.42                          |
| Linear rill length (m) per surface area >0.2 m/m².   |                    |                                 |                             |                            |                               |
| Eroded area in percentage %                           | 91.6               | 0.62                            | 1.80                        | 2.20                       | 1.92                          |
| Vegetation cover %, visual estimation.                | 8.4                | 31.4                            | 40.9                        | 87.4                       | 94.6                          |
| Degree of land transformation from the previous stage (before mining) (%) | -                  | 4.34                            | 4.34                        | 4.34                       | 4.34                          |

*Very high = 5, High = 4, Medium = 3, Low = 2, Zero = 1.

The geotechnical stability of the spoils depositions that are characterized by a wide Convex form was obtained by removing spoils mass from the upper part of the pile and moving it at the toe, reducing in such a way the slope angle, as well as by draining the entire mass of runoff and groundwater. The hydrological stability was achieved by covering all the area with topsoil of a depth of 40-50 cm, and the quick establishment of woody vegetation (mostly evergreen) with species characterized by dense and fibrous root system. In terms of landslide stability, all the restored area remained stable and without any experienced significant mass movement displacements during all the monitoring period of eight years due to the successful land transformation. Slopes of a medium inclination, slightly ranging from 21.6° to 23.6°, were the dominant topographical elements of the new post-mining land.

Analytically, the pre-mining land had a small percentage 12.1% of high inclination slopes (angle >30°), that was eliminated in the restored land. In contrast, the slopes of medium inclination (angle 15°-30°) were greatly increased after restoration, occupying the great percentage of the restored area (91.6%), compared to 47.3% occupied before mining. However, with this increase of medium inclination slopes, it seems that has no problems in slope stability. This increase of medium slopes mainly resulted from the reduction of the low inclination slopes (angle 1°-15°), which occupied a high percentage (40.6%) in pre-mining time, and it is zero after mining, as well as after restoration. Also, a part of this increase is coming from the slopes of high inclination, which were eliminated in the restored land. Finally, the restored land has a small percentage (8.4%) of flat areas formed at the top of the depositions. Considering all the above-mentioned, it can be concluded that the land transformation resulted in a new land form that presents some differences from the previous stage (before mining). Based on the approach of "approximate original contour" suggested by SMCRA, this new form, even though it differs from the natural contouring that existed before mining, is characterized by mild relief characteristics that imitate the surrounding terrain of the mined land.

Based on the data presented in Table 2, the degree of land transformation (DLD), according to equation (1), is equal to 4.34%. This estimated low value of the DLD indicates that the new land form does not present great differences from the initial land topography before mining, even though it is not the same.
Table 2. Distribution of slope inclination, before mining, after mining and before restoration, and after restoration works.

| Land condition                      | Flat areas (approximately 0° slope angle) | Slope inclination | | | |
|-------------------------------------|-------------------------------------------|-------------------|---|---|---|---|---|
|                                     | Area (ha) | % | Area (ha) | % | Area (ha) | % | Area (ha) | % |
| Before mining                       | 0.0 | 0.0 | 30.044 | 40.6 | 35.002 | 47.3 | 8.954 | 12.1 |
| After mining/ before restoration    | 6.2174 | 8.4 | 0.0 | 0.0 | 0.0 | 0.0 | 67.7826 | 91.6 |
| After restoration                   | 6.2174 | 8.4 | 0.0 | 0.0 | 67.7826 | 91.6 | 0.0 | 0.0 |
| Changes post-mining to pre-mining   | +8.4 | -40.6 | +44.3 | -12.1 |

Figure 3. (a) The mine depositions area before restoration works in 2007, and (b) The mine depositions during the first stage (land reformation and soil dispersion) of restoration works in 2011.

Figure 4. The mine depositions during the second stage (vegetation establishment through plantings) of restoration works in August 2012. Total eroded area (area within the blue line) = 4570 m² (0.46 ha).
Figure 5. The mine depositions two years after restoration works in 2014. Total eroded area (areas within the blue lines) = 13,343.4 m² (1.33 ha).

Figure 6. The mine depositions six years after restoration works in 2018. Total eroded area (areas within the blue lines) = 16,343.4 m² (1.63 ha).
Vegetation establishment and plant growth

Data on vegetation establishment, tree planted growth, and canopy closure are presented in Table 3. Data analysis shows that between the five main tree species planted (*Robinia pseudoacacia*, *Pinus brutia*, *Cupressus sempervirens*, *Cupressus arizonica*, and *Quercus pubescens*), the species *Robinia pseudoacacia* presented the better performance. This species is a nitrogen-fixing species suitable for mining restoration, and its use was the most abundant in the restoration project. Similar results for the species was reported by Panagopoulos and Hatzistathis (1995), in an electricity production lignite mine restoration, in an area (Ptolemaida, northern Greece) closed to the study area. According to the field data collected, the species exhibited quite high survival rates and high growth, reaching a mean height of 5.32 m, eight years after planting, and to a diameter of 6.85 cm. It has also greatly contributed to canopy closure (86.4%, eight years after restoration), which in turn helps in soil stabilization and prohibits soil erosion. The three planted coniferous species, *Pinus brutia*, *Cupressus sempervirens*, *Cupressus arizonica* presented also relatively good results, showing quite high survival rates and satisfactory growth (Table 3). The pine species *Pinus brutia* is the second most abundant species selected for the restoration, after *Robinia pseudoacacia*, and it also exhibited quite high survival and growth rates, as is shown in Table 3.
Table 3. Vegetation establishment data and growth of the planted trees, eight years after planting. Values are mean and standard error of mean (in parenthesis).

| Tree species              | Mean survival rate (%) | Mean height (m) | Mean diameter (cm) | N/ha        | Canopy cover (%)* |
|---------------------------|------------------------|-----------------|--------------------|-------------|-------------------|
| Robinia pseudoacacia     | 75.1 (8.7)             | 5.32 (0.46)     | 6.85 (0.49)        | 2503.1 (80.2) | 86.4 (6.4)        |
| Pinus brutia             | 63.5 (8.3)             | 2.96 (0.20)     | 4.98 (0.22)        | 1587.5 (61.2) | 72.5 (6.1)        |
| Cupressus sempervirens   | 65.8 (6.6)             | 3.31 (0.24)     | 4.23 (0.20)        | 1645.0 (67.4) | 60.8 (5.7)        |
| Cupressus arizonica      | 65.2 (7.2)             | 2.91 (0.25)     | 4.60 (0.26)        | 1630.0 (71.0) | 70.1 (6.0)        |
| Quercus pubescens        | 38.4 (5.1)             | 1.10 (0.80)     | 2.08 (0.09)        | 960.0 (44.5)  | 38.3 (4.8)        |

*The canopy cover concerns only that of the planted seedlings.

Finally, the species Quercus pubescens, a native deciduous oak that forms the woodland of the adjacent forest areas, was used in a low number, and it presented low survival (38.4%), and low growth rate. However, this is something common for most oak species when they are used in reforestation programs (Ganatsas and Tsitsoni, 2003). Other planted tree species recorded were Fraxinus ornus, Ostrya carpinifolia, Populus alba (at the lower part of the deposition area), and the shrub species Spartum junceum, Cotinus coggygria, Buxus sempervirens, Ligustrum vulgare and Phillyrea latifolia.

**Restoration effects on the concentration of asbestos fibers in air and water**

The restoration works greatly reduced the concentration of asbestos fibers in air (Figure 9) and water (Figure 10) in the restored parts of the mining area (depositions area). According to the data presented in Figure 9, it is clear that restoration greatly reduced the concentration of asbestos fibers in the air of mine depositions, resulting in a concentration lower than the limits of 0.01 fibers/cm³ for healthy air. However, in the water of the small artificial lake, created by mining in front of the quarry, the recorded values were always found slightly over the limits of $7 \times 10^6$ f/l, that set as standard values by EPA (Koumantakis et al., 2009), with some fluctuation between the different dates. This is due to the fact that restoration focused on spoils depositions and did not concern the quarry mining area.

**Improvement of landscape aesthetics**

Evaluation of the effect of restoration on the landscape aesthetics of the area was based on the modifications of the parameters that affected the visual absorptive capacity (VAC) of the landscape according to equation (2). VAC was estimated at the time before starting restoration, in 2007, and eight years after ending the restoration works, in 2020. Based on the data shown in Table 4, and by application the equation (2), VAC of the study area had the minimum value 4 degrees, before restoration. On the contrary, restoration greatly improved the values of all the factors, resulting in a high value of VAC of the landscape of the mining area. Thus, the extremely low value of 4 degrees of VAC before restoration, greatly increased to 36 degrees after the restoration works, which improved all the relevant factors (Slope inclination, Soil Erosion, Vegetation Regeneration Dynamics, C= Soil Color Contrast, and L= Landscape diversity).

![Asbestos fibres concentration](image-url)

**Figure 9.** Monitoring of concentration of asbestos fibers in the air (fibers/cm³) in the mine area, throughout the time; before restoration, though restoration and after restoration. It is clear that restoration greatly reduced the concentration of asbestos fibers in the air of mine depositions, and the values are below the permissible exposure limit (PEL) determined for asbestos in Europe (>0.01 f/cm³).
Figure 10. Monitoring of concentration of asbestos fibers in water \((\text{fibers} \times 10^6/\text{l})\) in the small artificial lake created by mining, throughout the time. The concentration remains dangerous (concentrations over the standard values set by EPA \((7 \times 10^6 \text{ f/l})\) (Koumantakis et al. 2009), since restoration focused on spoils depositions and did not concern the quarry mining area.

Table 4. Impacts of restoration works on factors affecting the visual absorption capacity (VAC) of the landscape of the study mining area.

| Factor                             | Conditions Values | Grade | Degree before restoration | Degree after restoration |
|------------------------------------|-------------------|-------|---------------------------|--------------------------|
| Slope Inclination (SI)             | 0-5%              | 5     |                           |                          |
|                                    | 6-15%             | 4     |                           |                          |
|                                    | 16-30%            | 3     |                           |                          |
|                                    | 31-60%            | 2     |                           |                          |
|                                    | >61%              | 1     |                           |                          |
| Soil Erosion (SE)                  | Low               | 3     |                           | 3                        |
|                                    | Medium            | 2     |                           | 1                        |
|                                    | High              | 1     |                           | 1                        |
| Vegetation Regeneration Dynamics (VRD) | High             | 3     |                           | 3                        |
|                                    | Medium            | 2     |                           | 1                        |
|                                    | Low               | 1     |                           | 1                        |
| Soil Color Contrast (SCC)          | Low               | 3     |                           | 3                        |
|                                    | Medium            | 2     |                           | 1                        |
|                                    | High              | 1     |                           | 1                        |
| Landscape Diversity (vegetation, topography, water sources) (LD) | High | 3 |                           | 3                        |
|                                    | Medium            | 2     |                           | 1                        |
|                                    | Low               | 1     |                           | 1                        |

**Discussion**

The environmental rehabilitation and ecological restoration of disturbed mine areas, especially those contaminated, such as in the presence of asbestos residues, is a difficult and complex procedure (Cornelissen et al., 2019; Lévesque et al., 2020). The Society for Ecological Restoration defined ecological restoration as the process of assisting the recovery of an ecosystem that has been degraded or destroyed (SER, 2002). However, even though in some cases an unassisted process of natural colonization can be effective, commonly, ecological restoration of mine areas requires systematic human assistance (Li, 2006). Especially for the cases, such as in the present study, where no restoration work has been done during the mining process, which resulted in the creation of a huge pile of spoils depositions area of 74 ha, and height of 180 m, an intensive and high-costly systematic human plan is extremely necessary.

The findings of the current study show that the application of the works included in the restoration plan in the depositions area of MABE asbestos mine in northern Greece resulted in effective land restoration.
transformation and stabilized all the disturbed area of mine depositions. Even the great difficulties of rehabilitation of the spoil peals that consist of non-structured materials of different sizes, which were unconnected to each other and had a height of 180 m, presented a high risk of landslide (Tsatsanifos et al., 2006), the restoration works succeeded to create a densely plant-covered network of land slopes of medium inclination and high stability. As mentioned before, the inclination of spoil peals surfaces was very steep (>70%) and faced continuous risk for damages from erosion and slides, depending on the current weather conditions. The reduction of the slope inclination of spoil peals has been achieved by the construction of the combination of wide and narrow terraces along the whole length of the slopes (Zagas et al., 2010). This, in turn, resulted in slope stabilization and the reduction of the erosive capacity of water and erosion mitigation. According to the data collected, the slopes inclination of the spoils depositions decreased to 21.6°-23.6° after the terraces construction (Figure 2). Additionally, the terraces functioned as the basis for revegetation. Revegetation works contributed to the minimization of soil erosion which was the main restoration goal (Tsatsanifos et al., 2006), while they served both to the elimination of the visual pollution of the area and by the creation of an (artificial) forest ecosystem in a short period of time (Lucas, 1991; Pamukcu and Simsir, 2006). The relatively high rates of trees survival and the high canopy closure of the woody vegetation resulted in effective protection of soils from erosion.

Although all the depositions slopes were restored using the same procedures, a small part of the area (approximately 2%, Table 1) faces soil erosion problems (rill erosion density over 0.2 m/m²), and presents rill network development. This problem is mainly derived from the topographic point where these areas exist, in the point of the greater pile height of 180 m, and huge amounts of overland flow generated in water-contributing areas found at the top of each slope. The continuous differences in past and current erosion rates between this part and the other slopes commonly produce notable differences in the development of reclaimed vegetation (cover, aerial biomass and litter) and in the accumulation of soil organic matter and total nitrogen (Moreno-de las Heras, 2009). This, in turn, results in important differences in the spatial distribution and establishment rate and growth of vegetation due to erosion-related interference on vegetation succession (Moreno-de las Heras et al., 2008).

The used tree species, such as Robinia pseudoacacia, which is a nitrogen-fixing legume tree species, and one of the most appropriate for poor soils and rehabilitation works (Zipper et al., 2011), presented high survival rates in all area planted, thus, covered the slopes, and mitigate soil erosion. The evergreen coniferous Pinus brutia also, is very dry resistant and very tolerant in poor soil conditions, and it grows naturally in the neighbouring forests, with its continuous foliage along the whole year, greatly helped in soil stabilization and improvement of landscape aesthetics. The deciduous oak Quercus pubescens grows in the wider area and is dominated in the disturbed area before mining (Zagas et al., 2010). Its use, even the relatively low survival rate, contributed to the ecological and aesthetic integration of the restored area into the general environment. The rest plant species used are secondary forest species that grow in the forests of the wider area and, for this reason, were planted in order to improve the biodiversity of the rehabilitated mining area. The dispersed topsoil in all mine depositions area in order to cover the spoil surfaces and hereupon help the planting and seeding success seemed to be a crucial factor that greatly contributed to the high revegetation rates. The visual absorption capacity of the landscape of the mining area was extremely significantly improved after the restoration works. The VAC was very low, 4 degrees, before restoration works and increased to 36 degrees after the proposed restoration. Taking into account that the vegetation cover is essential to stabilize disturbed sites (Wong, 2003), the choice of appropriate vegetation and type of planting stock was very important.

The great benefit from the restoration was the effective pollution restriction of the asbestos fibres. According to the pollution monitoring, the restoration works greatly decreased the concentration of asbestos fibers both in the air in the restored parts of the mining area (depositions area) immediately after ending the restoration works. Covering the spoils with an adequate quantity of topsoil and establishing vegetation are the two decisive measures that secure pollution avoidance (Tsatsanifos et al., 2006; Zagas et al., 2010). Finally, if we consider that according to the restoration plan, the aim of the future land use of the mining area was the establishment of a forest capable of protecting this ecologically sensitive mining area and protect the very important neighboring Polyphytou Lake, this goal seems to greatly succeed. Additionally, the ecological and esthetic incorporation of the mining area in the ecosystem and the landscape of the wider area has gradually happened.

Conclusions

The evaluation of the applied restoration works carried out by the current study showed that the mining area subjected to restoration is now characterized, eight years after restoration, by land stabilization, high woody vegetation cover, low erosion risk, and it was aesthetically integrated with the surrounding landscape. Even though the great difficulties due to the huge pile of spoils depositions, the selection of the specific restoration actions greatly contributed to the achievement of a sustainable post-mining environment. The suitable land transformation and the
satisfactory establishment of forest vegetation created a stable system and a safe from asbestos fibres environment, and for sustainable future land use of the previous mine area as forest, which in many cases is the most appropriate post-mining use for contaminated mining areas. This is in accordance with the overall goal of rehabilitation on asbestos mines worldwide, that of permanent elimination of the dispersion of asbestos fibres in air and water, and return the disturbed area to an ecologically stable state similar to pre-mining time. Additionally, the establishment of a forest ecosystem on mined land enhances diversity, improves soil quality, and protect the site from environmental degradation.

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