Heliyon 8 (2022) e09179

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

Active revegetation after mining: what is the contribution of peer-reviewed studies?

Silvia E. Navarro-Ramos [a,b,*], Javier Sparacino [a,c], Juan M. Rodríguez [a,b,c], Edith Filippini [a,b], Benjamín E. Marsal-Castillo [a,d], Leandro García-Cannata [a,b], Daniel Renison [a,b,c], Romina C. Torres [a,b,c]

[a] *Universidad Nacional de Córdoba, Facultad de Ciencias Exactas, Físicas y Naturales, Centro de Ecología y Recursos Naturales Renovables, Av. Vélez Sarsfield 1611, X5016GCA, Córdoba, Argentina*

[b] *Instituto de Investigaciones Biológicas y Tecnológicas (IIByT-CONICET-Universidad Nacional de Córdoba), Av. Vélez Sarsfield 1611, X5016GCA, Córdoba, Argentina*

[c] *NGO Ecosistemas Argentinos, 27 de abril, 2050, Córdoba, Argentina*

[d] *Instituto de Diversidad y Ecología Animal (IDEA-CONICET- Universidad Nacional de Córdoba), Av. Vélez Sarsfield 299, X5000JJC, Córdoba, Argentina*

HIGHLIGHTS

- Most of the studies on post-mining active revegetation were performed in temperate climates.
- The most widely evaluated treatments were the addition of amendments and fertilizers.
- The effectiveness of the treatments varied plant species and the local context.
- Organic amendments were the most effective treatment based on indicators of plant performance.

ARTICLE INFO

Keywords:
Establishment
Mine
Planting
Rehabilitation
Sowing
Treatments

ABSTRACT

Knowing the state of the art on research related to post-mining active revegetation can help to improve revegetation success and identify research gaps. We performed a systematic review about active revegetation after mining and identified 203 relevant studies. Most studies were performed in the USA (34%), in regions with a temperate climate (59%) and in abandoned coal mines (45%). The studies were focused on the plantation of woody species (59%) or sowing of herbaceous species (39%). The most widely evaluated treatments were the addition of amendments (24%) and fertilizers (21%), mainly with positive and neutral effects; in general, organic amendments presented more positive effects than inorganic amendments and fertilizers. We also identified studies on the effects of plowing, inoculation of microorganisms, nurse plants, herbivore exclusion and watering. The results of these treatments should be taken with caution, because they can vary according to the functional strategies of the introduced species and the local context, such as the degree of nutrient limitation in the mining area and abiotic conditions. Further research is needed in non-temperate climates, involving long-term monitoring and with detailed descriptions of the interventions to better interpret results and general implications of active revegetation of mining areas.

1. Introduction

Mineral demands for multiple purposes have increased in the last centuries, with mining activities causing profound alterations that can persist for a long time after mine closure (Kesler, 2007). Mining destroys the vegetation and soil profile, not only through soil excavation for mineral extraction but also through waste deposition; thus, mining generates particularly stressful conditions, such as nutrient depletion and poor physical structure of the substrate, which slow down vegetation establishment (Di Carlo et al., 2019).

Revegetation has an important role in reversing degradation processes in areas that have been subject to mining activities. Plants help to protect the soil from erosion through the development of the root systems, which stabilizes the soil and reduces its compaction. Moreover,

* Corresponding author.
E-mail address: silnara134@gmail.com (S.E. Navarro-Ramos).

https://doi.org/10.1016/j.heliyon.2022.e09179
Received 6 October 2021; Received in revised form 24 December 2021; Accepted 18 March 2022

plant aboveground biomass protects the soil from the action of rain and wind, increases soil organic matter, and forms micro-reliefs that reduce surface runoff, favouring the infiltration of water into the soil (Favero-Longo et al., 2009; Li et al., 2014).

Active revegetation practices in sites degraded by mining include the introduction of plants through sowing and planting, in some cases after the reconstitution of the topsoil (Plamping et al., 2016; Torroba-Balmori et al., 2015). Another practice is passive regeneration, which consists of spontaneous vegetation recovery with no interventions of any type after abandonment of mines and active revegetation without soil reconstitution (Frouz et al., 2015; Spargo and Doley, 2016). Passive regeneration is sometimes chosen for conservation reasons, because spontaneous recovery may lead to increased biodiversity (Kirmer et al., 2008; Prach and del Moral, 2015). Other times, active revegetation without soil reconstitution is used because reconstitution of the topsoil is complex, expensive and, in many cases, unsuccessful (Frouz, 2021; Šebelíková et al., 2016). Legislation in some countries requires the salvage and stockpiling of topsoil for later use during revegetation (Hu, 2014). Native topsoil can improve the soil physical, chemical and biological characteristics, and helps succession of native vegetation through the seed bank (Hall et al., 2010; Macdonald et al., 2015). However, the topsoil, consisting of the A-horizon, is a scarce resource; indeed, in some regions, it can be a few centimeters in depth (Darmody et al., 2009). Moreover, topsoil is hardly ever stored for reuse in mined lands; instead, it is usually borrowed from nearby areas, causing further degradation (Sheoran et al., 2010). When topsoil is stored for reuse, the time spanned between its initial removal and its final deposition on the reclaimed area can be long; thus, soil properties deteriorate, until the soil becomes biologically non-productive (Sheoran et al., 2010).

Vegetation establishment after mining can be difficult due to severe limitations of soil properties caused by mining activities. Soil removal for mineral extraction and waste deposition generates open areas of bare soil without organic matter, soil compaction and high exposure to weathering agents (Clemente et al., 2004). These open areas have low capacity to retain seeds until germination; the few seeds that are retained are subjected to highly stressful environmental conditions for germination and establishment due to the lack of nutrients and soil microorganisms, and to water stress (Espigares et al., 2011). Vegetation establishment also depends on the availability of seed sources near the mined area and on the presence of seed dispersers. Thus, the degree of isolation of the mined area can play an important role in vegetation recovery (Milder et al., 2013), and vegetation recovery without human intervention may be a slow process. Active revegetation may be a good option, even without soil reconstitution, since different factors can be managed to drive plant communities to desired goals (Holl and Aide, 2011). However, the decision on the use of passive or active revegetation will depend on the specific goals of the revegetation project, the social and economic aspects, and the specific conditions of the site (Masoumi et al., 2014; Mborah et al., 2016; Prach et al., 2020).

Managers can apply different techniques to increase plant establishment, ranging from the selection of plants with desired characteristics to the application of treatments, such as watering and amendments. Plant selection involves type of vegetation and specific species to be used, and will depend on the main goal of revegetation, which could be to stabilize terraces, control soil erosion, recover plant community, or even improve the aesthetics of the area (Lei et al., 2016; Lima et al., 2016). In some cases, plants used in revegetation projects are those locally available, favoring native and locally adapted species (Pedrini et al., 2020). In other cases, revegetation projects take advantage of commercial seed mixtures, which may contain non-ecologically selected species or potentially invasive non-native species (Martínez-Ruiz et al., 2007; Skousen and Zipper, 2014). Moreover, both the selection of plants and the application of treatments to improve plant establishment in mined lands can be focused on accelerating plant cover and retaining soil, regardless of the recovery of biodiversity and successional processes (Hernandez-Santin et al., 2019).

The Society for Ecological Restoration defined ecological restoration as "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed", and described the aims of ecological restoration as "to move a degraded ecosystem to a trajectory of recovery that allows adaptation to local and global changes, as well as persistence and evolution of its component species" (SER, 2004). In this sense, ecological restoration based on the knowledge of the local ecosystem may provide successful results. However, there are major knowledge gaps and, therefore, restoration actions use the best "tools at hand", such as species available in the market or cost-effective techniques adapted to the available and usually limited time and resources (Aronson et al., 2010). Thus, ecological restoration research is also driven by existing restoration experiences based on available resources rather than on the ecological basis of natural succession of the ecosystem (Falk et al., 2016). For this reason, it is crucial to identify and quantify the practices and treatments that have been investigated. Since mining is a widespread activity and vegetation establishment after mining is a complex process, it is important to determine if research on mining site restoration has encompassed a wide range of treatments to improve plant establishment or if some aspects, such as the role of biotic interactions on establishment, have been poorly considered. Knowing the state of the art about active revegetation after mining around the world can help to identify well established successful practices and therefore drive future research to improve the success of mining site restoration.

In this study, we performed a systematic review of the peer-reviewed literature on active revegetation after mining to identify the main research trends and gaps. We analyzed 203 peer-reviewed published studies and attempted to answer the following questions:

(1) What is the context of the active revegetation research regarding countries, climate regions and types of mineral extracted?
(2) What is the most frequent type of active revegetation –in terms of sowing and planting– addressed in published studies? What practices have revegetation studies focused on in relation to life forms and species origin? Which treatments to improve vegetation establishment have been studied and which ones have been understudied?
(3) What treatments have been applied with most frequent positive results in terms of plant establishment, survival and growth?

After answering these questions, we discuss the lessons learned from this review and make recommendations for further research based on the treatments that we identified as possible tools to improve active revegetation after mining. To the best of our knowledge, this is the first systematic review addressing these topics.

2. Materials and methods

We performed a systematic review of the scientific literature in July 2017, following the method proposed by Pickering and Byrne (2014). A database of studies about active revegetation after mining activities published in English was obtained by systematically searching the web using Google Scholar, ISI Web of Science and Scopus databases (Figure 1).

Our search was based on three groups of keywords linked with the operator AND: (1) Keywords of the restoration processes (*establish* OR succession* OR *colonize* OR regeneration OR rehabilitation OR rest* OR claim); (2) Keywords of the organism to be restored (*vegetat* OR wood* OR shrub* OR herbaceous OR bush*); (3) Keywords of the disturbance before restoration (quarr* OR mine OR extraction OR extracted). The truncation symbol "*" was used to retrieve citations including a root word.

After the literature search, we selected studies based on the relevance of the title and abstract; whenever necessary, we assessed the full text before making a decision on selection. We included studies describing results after an active *in situ* revegetation on terrestrial

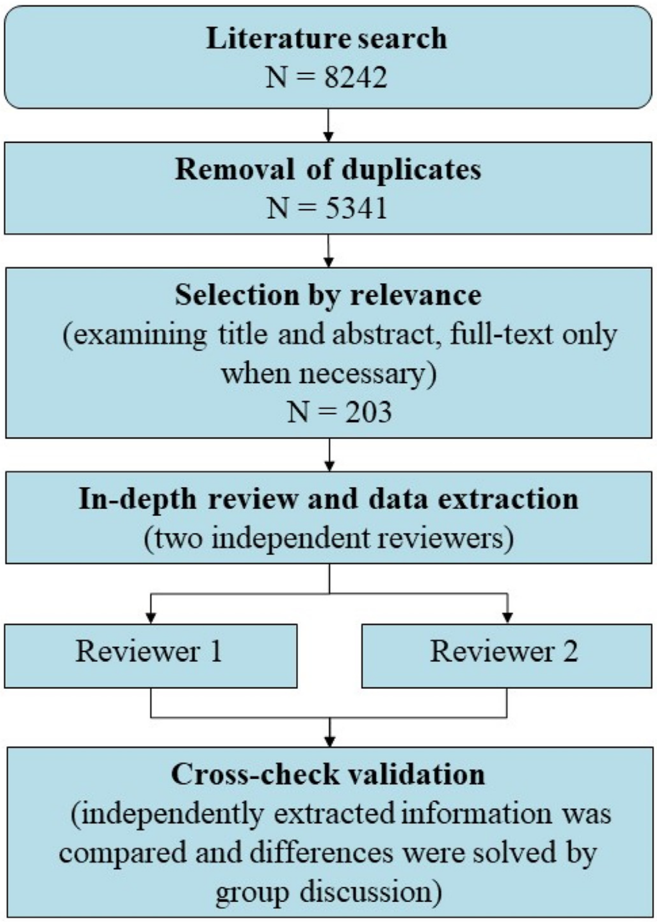

Figure 1. Flow chart of the methodology used for database construction. N: number of studies selected at each step (see main text for details).

mined areas without reconstitution of the organic horizon, namely without topsoil reconstitution. We considered active revegetation those activities such as planting or sowing of vascular plants at sites affected by mining activities, both at extraction sites and spoil heaps. We excluded studies that: (a) focused only on spontaneous vegetation establishment; (b) described research conducted in greenhouse or experimental areas, because we considered only *in situ* restoration; (c) located in aquatic or sub-aquatic environments, such as mangroves, beach dunes, peat bogs and wetlands; (d) related to the uptake of pollutants by vegetation; and (e) did not analyze results using inferential or descriptive statistics.

After the selection process, a total of 203 studies were included in a database for review and analysis (Appendix A1). Studies were analyzed independently by two reviewers; disagreements were solved through group discussion (Figure 1). The information extracted from each study was classified into three categories:

(1) *Context of the research:* (a) year of publication; (b) country where the restoration was carried out; (c) climatic zone using the geographic coordinates of the mine or of the midpoint between mines whenever more than mine one was involved. The climate was identified using the Köppen classification (Köppen, 1936), which recognizes five principal groups of world climates (dry, continental, tropical, temperate and cold); (d) type of extracted mineral, considering the following 13 groups: building materials, calcium derivatives, clay and sedimentary rocks, igneous rocks, metals, metamorphic rocks, mineral coal, mineral mix, oil sands and shale, phosphates, precious stones, rocks and serpentine minerals; (e) Year of vegetation introduction; (f) year of cessation of mining activities; and (g) interventions made in the area before plant introduction.

(2) *Practices of active revegetation:* (a) type of introduction (sowing/planting); (b) life form of the introduced plants (herbaceous/woody); (c) origin of the introduced plants (native/non-native); (d) treatments implemented to improve vegetation establishment; (e) number of species used in the study; and (f) number of mines involved. Regarding the treatments implemented to improve vegetation establishment, we classified them into five groups: (i) treatments applied to the soil: fertilization, application of amendments (organic and inorganic) and mechanical treatments such as plowing. We also included studies that assessed revegetation success among different types of soil, topographies, slopes and degree of soil compaction; (ii) watering and hydrogel application; (iii) treatments that included manipulation of the vegetation surrounding the target plants, such as nurse-based planting/sowing, herbicide application, weed control and herbivore exclusion; (iv) treatments applied to seeds and saplings before the introduction of the plants in the field, including inoculation of microorganisms such as mycorrhiza and bacteria, and the application of fungicides and seed coating; and (v) treatments based on the use of different sowing and planting techniques, such as different depths of sowing, planting seasons and sowing/planting densities.

(3) *Success of most frequently implemented treatments*: (a) number of species with positive, negative and neutral results reported in the study; (b) monitoring time in months; (c) indicator of plant performance (response variable), e.g. plant cover of sown species, survival of planted saplings, etc.

3. Results and discussion

3.1. Context of reviewed research

The 203 studies reporting active revegetation after mining without soil reconstitution were published between January 1979 and July 2017. The number of studies increased over time, from 2 in 1979 to 14 in 2016, with a high number of them having being published between 2009 and 2016 (Figure 2). Wortley et al. (2013) reported a similar increase in the number of studies assessing ecological restoration success as of 1990, with a greater increase of studies having been published in the last four

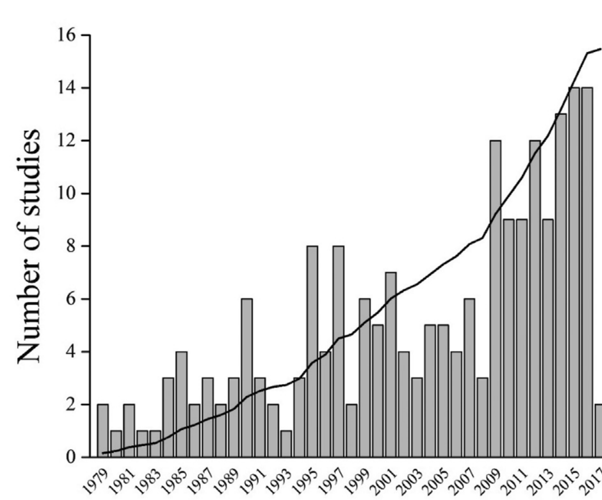

Figure 2. Number of studies identified through the literature search per year of publication. Gray bars (left Y-axis) represent the absolute number of reviewed studies per year. The black line (right Y-axis) represents the cumulative number of studies per year. Note: the literature search in 2017 includes works published up to July (N = 203).

years of the reviewed period. In addition, in recent years mining activities have increased due to a growing use of digital technologies (UNCTAD, 2020). Therefore, the increase of active revegetation studies has responded to the need to mitigate the impact of these activities.

The studies were published in 100 different journals, reflecting the trans-disciplinary interest in this topic. Thirty-three journals accounted for 67% of the total number of studies. The most representative journals were Ecological Engineering (8.4%), Restoration Ecology (7.4%), International Journal of Surface Mining, Reclamation and Environment (6.4%) and Journal of Applied Ecology (5.4%). Other journals were represented by five or fewer studies (<2.5%) (Appendix A2).

The studies were distributed in 33 countries. The leading country was the USA (69 studies, 34% of the total number), followed by China (18 studies, 9%), Canada (17 studies, 8%), India (17 studies, 8%), and Australia (11 studies, 5%). A total of 15 countries were represented with one study (Figure 3). The USA, Russia and China are among the countries with the highest mineral extraction (U.S. Energy Information Administration, 2019). However, Russia and China were not represented with a high number of studies in comparison with the USA, indicating that the mineral extraction rates per se are not enough to explain the number of studies. In the USA, there are laws dating back to 1977 that oblige mine companies to perform after-mining restoration of the vegetation cover (Macdonald et al., 2015); this fact may help to explain the high interest in the topic in the scientific community. Other countries with intense mineral extraction, such as China and Russia, also have laws regulating mine reclamation since 1986 and 1968, respectively (Bond and Piepenburg, 1990; Cheng and Skousen, 2017); however, in practice, this legislation is not enforced (Cao, 2007; Faizuldayeva, 2016). Countries with greater compliance with restoration laws are likely to make greater investments and be more interested in restoration research to contribute to the success of reclamation initiatives. However, it should be noted that results could be language-biased. If we assume that implementers very often do not understand foreign languages and that researchers are interested in reaching that audience, an important amount of articles may be published in the local language and those countries with language other than English would be under-represented in our analysis. Furthermore, our results may be influenced by the fact that the USA is one of the countries that publishes the highest number of peer-reviewed articles on ecological restoration (Aronson et al., 2010).

Most of the surveyed research was carried out in regions with temperate climate (119 studies, 59%), mainly because this is the prevailing climate in the USA. Plant germination, survival and growth could be hampered by harsh abiotic conditions in some temperate climates (Pueyo and Alados, 2007; Shriver et al., 2018). Seasonally dry ecosystems in the USA are particularly vulnerable due to low and variable precipitation, and the invasion by non-native species (Evans et al., 2013; Andrus et al., 2018). The need for restoration in these ecosystems could partially explain the higher number of studies conducted in temperate climate regions than in other regions (Copeland et al., 2018). A lower success of passive restoration in terms of species composition is reported in areas with tropical climates than in those with temperate climates (Prach and Walker, 2019). However, in tropical climates, plant establishment and vegetation recovery (in terms of plant cover) can be faster than in temperate climates because precipitations and temperature are higher than in other climates, which implies higher growth rates (Novianti et al., 2018). This could partially explain the lower number of studies in tropical areas. Furthermore, UNESCO Science Report (2010) indicates that the governments of countries with a tropical climate, such as Brazil and Indonesia, invest little in research and development (low gross domestic spending in research and development relative to gross domestic product). Therefore, the lack of economic resources to do research may also influence the number of studies found in areas with tropical climate.

Most of the reviewed research works involved coal mines (45%, 91 studies), followed by metal mines (27%, 55 studies), and mines exploiting clay and sedimentary rocks (8%, 17 studies), and calcium derivatives (7%, 14 studies). The other nine mineral groups were represented by four or fewer studies each, and seven studies (3%) did not inform the type of mineral that had been extracted in the revegetated area. Coal is widely used as a fuel source to generate electricity in the USA. It is also used in the production of steel, cement, and for home and commercial heating throughout the world (USGS, 2019); therefore, it is not surprising that coal is one of the most widely represented minerals in the reviewed studies.

After-mining introduction of vegetation with no direct assessment of plant performance was reported in 58 of the 203 studies (29%). These studies focused on the monitoring of plant community development in terms of biomass and changes in floristic composition (Figure 4). Assessment of the introduced plant performance after sowing or planting was reported in 145 studies (71%). Success was evaluated in terms of plant survival and growth, among other indicators of plant performance (Figure 4).

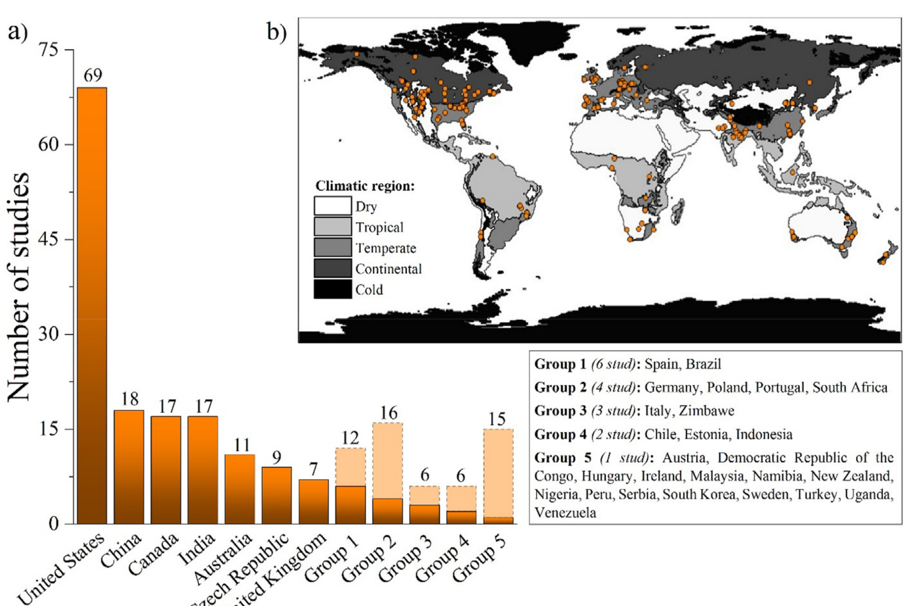

Figure 3. Distribution of reviewed studies by country and climatic region. a) Number of studies reviewed by country. To synthesize the data, countries with the same number of studies were grouped (Groups 1 to 5). For example, Group 1 includes Spain and Brazil, with six studies each, totaling 12 studies. Group composition is described in the box (in parentheses, the number of studies per country). Dark and light orange bars represent the number of studies per country and the total number of studies per group, respectively. The numbers above the bars represent the number of studies per country or group of countries. b) Map of global distribution of studies on active revegetation after mining. Climatic regions follow Köppen classification (Köppen, 1936) (N = 203).

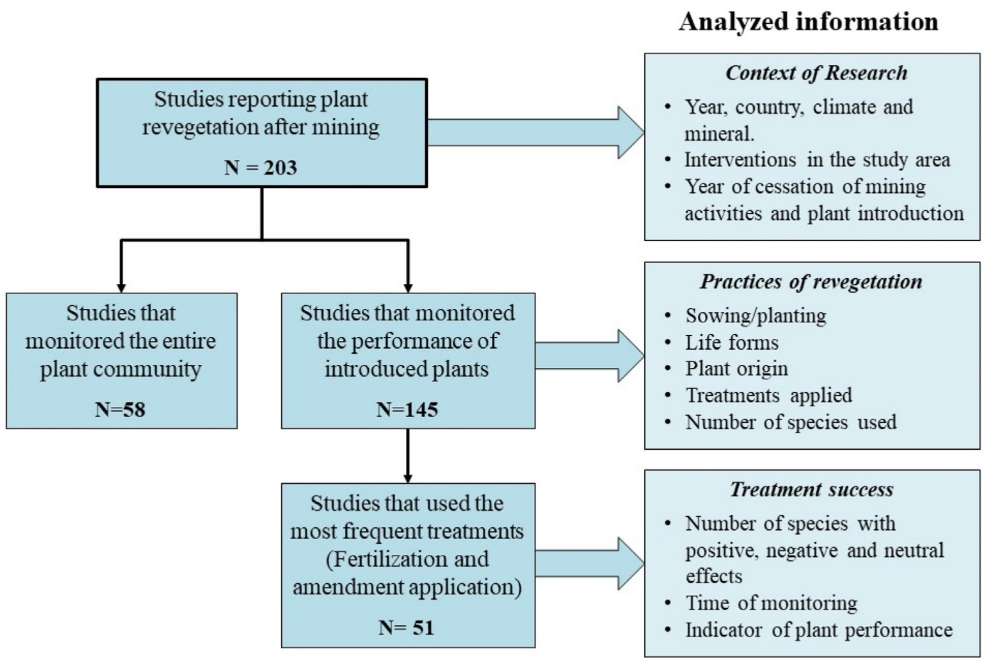

Figure 4. Flowchart showing the number of studies in the main categories into which they were classified and information obtained from each study.

Most studies did not provide detailed information of the year of cessation of mining activities or the year of plant introduction (155 of the 203 studies, 76%). Therefore, it was not possible to determine the period between the cessation of mining activities and plant introduction and, as a consequence, made it difficult to interpret the role of plant introduction in vegetation recovery after mining. The time elapsed since the cessation of mining activities affects the arrival of propagules and the establishment of a plant community dominated by opportunistic native or non-native species (Trepanier et al., 2021). In some cases, plants were introduced for research purposes by a team other than the mining company. Thus, detailed information about the cessation of mining activity in some cases is difficult to acquire and, therefore, not reported (Hernandez-Santin et al., 2019).

3.2. Practices of active revegetation

We identified 145 studies that assessed the performance of the introduced plant. Most studies were focused on the plantation of woody species (86 out of 145 studies, 59%) or sowing of herbaceous species (56 out of 145 studies, 39%), whereas a few studies focused on the plantation of herbaceous species or the sowing of woody species (Figure 5). Planting trees after mine closure, mainly pine species, was a common practice between 1940 and 1970 in the USA, even in a context of no legal requirements and little emphasis on revegetation, with the only intention to rehabilitate the land (Skousen and Zipper, 2014). In Australia, planting pine and eucalyptus species was also the most extended practice for mine revegetation before 1980 (Grant and Koch, 2007). In India, reclamation with tree plantation has also been a common practice among mining companies (Kumari and Maiti, 2019). In the USA, sowing herbaceous species, i.e. grasses and clover, was the most extended after-mining practice in the 1980s and 1990s, with the aim to stabilize the soil and develop pastures for livestock grazing over a short period and at low cost (Skousen and Zipper, 2014). In the Mediterranean region of Spain, hydroseeding with herbaceous plants was also widely used (Oliveira et al., 2013). The extensive use of these practices can mostly explain a greater number of studies focused on the plantation of woody species and the sowing of herbaceous species, in comparison with the few studies on the plantation of herbaceous and the sowing of woody species. Moreover, sowing woody species usually results in low establishment rates, mainly in degraded areas with severe biotic and abiotic limitations (Carabassa et al., 2019).

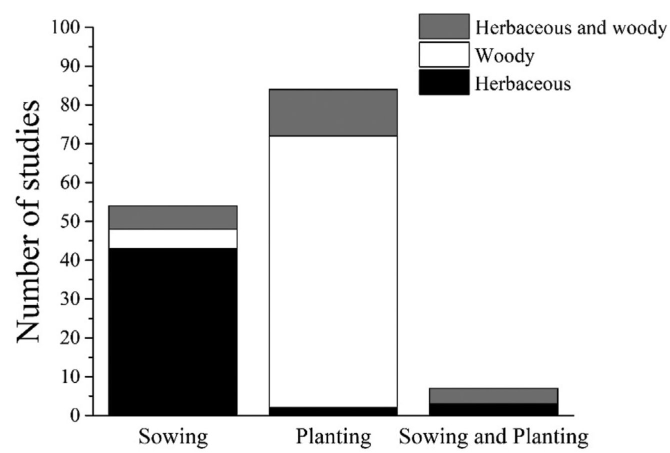

Figure 5. Number of studies focused on sowing and/or planting, and life form of the introduced species (herbaceous or woody), of a total of 145 studies that assessed the performance of the introduced plants.

Concerning the origin of the introduced species, 65 of 145 studies (45%) use mainly native species, 14 (10%) use non-native species, and 82 (57%) did not report the origin of the introduced species. Since some studies used multiple species, native, non-native or undetermined species, the total exceeds 100%. Using native or non-native species is a very important issue, since plant invasion of non-native species is one of the global concerns for biodiversity conservation (Foxcroft et al., 2017). Non-native plants can prevent the establishment of native woody and herbaceous plants, and can cause changes in hydrological or disturbance cycles, i.e. fire regimes, with permanent consequences on successional trajectories (Kirmer et al., 2012). The reasons for using non-native species for after-mining revegetation can be related to their lower cost than that of native ones, their availability in the market and their fast plant establishment to achieve soil retention. Thus, soil erosion is prevented and laws regarding the cessation of mine activities are complied with (Bochet et al., 2010). A few well-studied species, usually highly competitive grass and legume species, e.g. *Festuca ovina*, *Trifolium pratense* and *Cynodon dactylon,* are usually used for these purposes. They are included in low diversity commercial mixtures to revegetate mining areas (Martínez-Ruiz et al., 2007). Some of these species are invasive outside their natural distribution range, like *Cynodon dactylon*, which is naturally distributed in Africa and southern Europe, and highly invasive in some areas of southern USA (Farthing et al., 2018). In recent years, increased emphasis has been given to the importance of using native plants adapted to the local climatic conditions, which has increased success in reforestation and conservation of local biodiversity (Macdonald et al., 2015).

Interventions made before the introduction of vegetation were mentioned in 80 out of 145 studies (55%); they were aimed to improve unfavorable soil conditions, including amendment application, fertilization, plowing and irrigation, and to ameliorate biotic limitations, such as herbivore exclusion and herbicide application. Those interventions were not the focus of the studies and, consequently, were not evaluated; however, they may have had a crucial role in the success of subsequent revegetation. In some cases, these interventions were part of mine closure operations and were performed many years before the study.

Regarding the treatments to improve vegetation establishment that were assessed in the studies, the most widely evaluated treatment was the addition of amendments (48 studies, 33%). Of those 48 studies, 24 (17%) used only organic amendments, such as waste compost, manure, peat, cellulose fiber, and wood debris; and 5 studies (3%) used only inorganic amendments, like lime, sandstone and marl. A total of 19 studies (13%) involved both organic and inorganic amendments. Amendment applications can increase soil water retention capacity and porosity, reducing some widespread soil limitations in mined lands and increasing vegetation growth (Li et al., 2019; Macdonald et al., 2015). The second most widely evaluated treatment was the use of inorganic fertilizers, such as NPK, nitrates, phosphates and ammonium (42 studies, 29%). Fertilizers help initiate nutrient cycling processes and stimulate the growth of implanted vegetation in degraded areas (Ortiz et al., 2012). The third most widely evaluated group of treatments included those that made interventions in the soil (e.g. plowing, the use of different types of soil or different topographic characteristics, such as slope and aspect) inside the mine to carry out sowing and/or planting (32 studies, 22%). Plowing is widely used to reduce compaction and increase water retention, infiltration, and root growth, all of which improve plant survival and growth, especially in dry years (Angel et al., 2018). Slope and aspect can influence the establishment of vegetation through variations in solar radiation, soil humidity and water stress (Alday et al., 2010).

A total of 31 studies (21%) compared plant performance of different species after their introduction. Species selection is an important aspect in many restoration projects; however, basing species selection only on fast plant implantation may be detrimental to other important factors, such as adaptation to site conditions or species origin (Gastauer et al., 2018).

A set of treatments were based on taking advantage of positive interactions or on avoiding negative interactions between organisms. These treatments, which were applied to seeds and/or saplings before sowing and planting in the field, respectively, were evaluated in 17 studies (12%), including inoculation of microorganisms and fungicide application. The inoculation of microorganisms such as mycorrhizal fungi and rhizobia improves nutrient absorption, nitrogen fixation and stress tolerance of host plants (Matias et al., 2009; Navarro Ramos et al., 2018). Soil pathogenic fungi often cause seed mortality; therefore, the application of fungicides to seeds can help increase seed survival (Hou et al., 2021). Treatments that included the manipulation of the vegetation surrounding the target plants, such as the use of nurse plants, weed control and herbivore exclusion, were assessed in 15 studies (10%). It is well established that plant-plant interactions and plant-animal interactions greatly influence plant establishment (Van Andel, 2005). Positive plant interactions can be used to optimize the performance of introduced vegetation (Torres and Renison, 2015). Likewise, decreased competition can be necessary to improve plant survival and growth; thus, weed control can be a good alternative to favor vegetation establishment (Passaretti et al., 2020). Herbivore incidence can also limit the establishment of plants and the subsequent regeneration of the ecosystem; therefore, herbivore exclusion can reduce the negative effects on revegetation (Torres and Renison, 2015).

Different sowing and/or planting techniques, such as sowing at different depths and planting in different seasons, were analyzed in 14 studies (10%). Plant performance at early stages of establishment, i.e. germination and early survival and growth, is highly dependent on soil conditions, like humidity and temperature, which are highly variable in different seasons, especially in degraded areas (Ottavini et al., 2019). A total of 12 studies (8%) compared plant performance at different times after vegetation introduction. Vegetation monitoring over time is rare in the reviewed papers, even though plant performance can change over time in accordance with resource availability and stress tolerance of the introduced species (Schiffers and Tielbörger, 2006). Watering and/or hydrogel application after plant introduction was assessed in 10 studies (7%). The importance of water stress on plant performance depends on several factors such as climate and substrate types (Zettl et al., 2011). However, water stress can be a limiting factor not only in arid ecosystems but also in most of the regions with a dry season (Mediterranean and Monzonic regions), even where annual precipitation is high, e.g. in some seasonally dry tropical and subtropical forests. Additionally, in degraded areas water stress increases due to the changes in soil structure and composition (Abella et al., 2015). However, the effect of watering and/or hydrogel application on plant performance has been poorly studied, probably due to the high cost of applying irrigation in post-mining areas, which are often far from a water source (Josa et al., 2012). Finally, two studies (1%) evaluated the effect of the distance to the nearest forest and one study (0.7%) tested the influence of different climatic regions (with variations in temperature and humidity) on vegetation (Figure 6).

3.3. Success of the most frequently implemented treatments

In the last part of our analysis, we focused on the effects of the two most frequently reported treatments, i.e. fertilizer and amendment application, on plant performance. Therefore, the relevant articles were reduced to 51 studies (Figure 4). The used success indicators are detailed in Table 1.

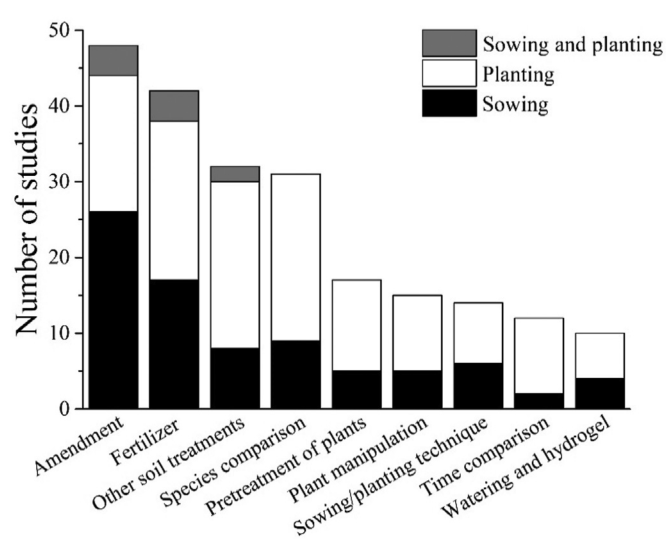

Figure 6. Number of studies assessing the effect of different types of treatments on plant performance after sowing, planting, or sowing and planting (one study may include multiple treatments) of a total of 145 studies that assessed the performance of the introduced plant.

Table 1. Indicators of plant performance used in 51 sowing and planting studies evaluating the success of the most frequently implemented treatments.

Variable	Indicator	Number of studies
Sowing success	Proportion of plant cover	18
	Dry mass	14
	Plant density	8
	Number of emerged plants	2
	Maximum height of plants	2
	Individual height	1
	Stem basal diameter	1
	Crown width	1
Seedling growth	Height increment	18
	Stem basal diameter	12
	Dry mass	8
	Proportion of plant cover	2
	Canopy width	1
	Crown width	1

Besides the 51 studies described here, 13 other studies that assessed fertilizer and amendment application did not include an untreated control or applied two or more treatments simultaneously; therefore, we cannot clearly categorize the results as positive, negative or neutral. The effects of fertilizers and amendments reported in these 51 studies are shown in Table 2. Regarding sowing of herbaceous species, most studies reported positive or neutral effects of the application of inorganic fertilizers, organic amendments and inorganic amendments, whereas a few studies reported negative effects. With respect to the survival of planted woody species, most studies reported neutral effects of inorganic fertilizers and inorganic amendments, whereas for organic amendment application, a similar number of studies reported positive and neutral effects, and a few studies reported negative effects. Concerning the growth of planted woody species, most studies reported positive and neutral effects of inorganic fertilizers and organic amendments, whereas for inorganic amendment application most studies reported neutral effects, and only a few studies reported negative effects.

Considering the great impact of mining activities on the soil, we expected that treatments that added organic matter and nutrients to the soil, such as fertilization and amendments, would improve vegetation establishment. However, surprisingly, many studies reported neutral effects. This finding could be due to several reasons. On the one hand, the effect of fertilization and the addition of amendments may depend on the functional strategies of the introduced species, since plants differ in biomass allocation when there is an increase in nutrient availability (Oliet et al., 2013; Ploughe et al., 2021). Unlike late-successional species, pioneer species tend to allocate more resources to aerial parts than to roots (Portsmuth and Niinemets, 2007); thus, the effect of nutrient addition can depend on the indicator used to assess growth. In addition, the effects of these treatments may benefit neighboring plants, which compete for resources with the implanted vegetation. Therefore, the negative effects of neighboring plants on the performance of the treated vegetation are probably offset by the positive effects of fertilization or the addition of amendments, resulting in neutral or negative effects on the establishment of the treated vegetation (Soliveres et al., 2012). The neutral effects of some inorganic amendments, such as gypsum and lime, can be also explained by the long time they take to dissolve; therefore, nutrients become available a long time after their application, with their effect on vegetation growth possibly being significant several years later (Reid and Naeth, 2005). In contrast, organic amendments and inorganic fertilizers are available in the short- and mid-term, showing positive effects earlier than inorganic amendments (Antonelli et al., 2018). Furthermore, the success of fertilization and amendments may vary with the context, such as the degree of nutrient limitation in the mining area and local abiotic conditions. It is known that the lower the nutrient amount in the soil, the greater the absorption by the vegetation after nutrient addition (Harrington et al., 2001). Local abiotic conditions, such as rainfall and temperature, also influence the success of amendments and fertilizers. Leaching from fertilizers can increase with increasing rainfall and temperatures (Jabloun et al., 2015). In addition, organic amendments are more effective in warmer climates, since nutrients are mineralized faster and may be available to plants more rapidly (Ploughe et al., 2021). In turn, in semi-arid climates, where rainfall is scarce, rapid nutrient mineralization can lead to increased salinity and, consequently, water stress (Fuentes et al., 2007). Finally, application rates may have also influenced the results. It is known that low or very high nutrient application rates can have neutral or negative effects on vegetation establishment (Fuentes et al., 2010). Only a few studies reviewed here tested different rates of fertilizers and amendments on vegetation in order to identify the most appropriate dose.

In the 51 studies assessing plant performance after the application of fertilizers and amendments, monitoring time ranged from 2 to 360 months. Of them, 37 studies (73%) monitored plant performance for 36 months (three years) after revegetation. This period is used in many plant establishment studies (Gómez-Aparicio, 2009) and is considered appropriate to understand the most vulnerable phases of establishment and to assess the accomplishment of revegetation goals in mined areas, such as fast soil cover and prevention of soil erosion (Herrick et al., 2006). However, long-term monitoring can be necessary to assess successional trajectories after the introduction of plants (Macdonald et al., 2015).

The number of species assessed per study ranges from 1 to 54; however, 40 of the 51 studies (78%) evaluated between 1 and 6 species. Importantly, several studies focusing on the performance of sowing herbaceous plants did not distinguish between introduced and non-

Table 2. Number of studies reporting positive (+), negative (-) or neutral effects on plant performance after fertilizer or amendment application. Numbers between brackets represent the total number of species evaluated in all studies of each group. Number of species preceded by a ">" indicates an unknown higher number due to the use of a mixture of species.

Plant performance	Effect	Treatments					
		Inorganic fertilizer		Organic amendment		Inorganic amendment	
		Herbs	Woody	Herbs	Woody	Herbs	Woody
Sowing success (cover, biomass, density)	+	8 (>41)	1 (>1)	11 (>23)	1 (>1)	5 (>7)	1 (1)
	-	1 (3)	0 (0)	2 (>5)	0 (0)	0 (0)	1 (>1)
	Neutral	5 (>8)	0 (0)	7 (>74)	0 (0)	6 (>26)	0 (0)
Seedling survival (proportion of live individuals)	+	1 (1)	1 (3)	0 (0)	6 (15)	1 (1)	1 (4)
	-	1 (2)	1 (3)	0 (0)	2 (2)	0 (0)	0 (0)
	Neutral	1 (8)	11 (35)	0 (0)	8 (22)	1 (9)	4 (14)
Seedling growth (biomass, cover, diameter increase, height increase, dry mass)	+	1 (1)	8 (19)	0 (0)	8 (19)	0 (0)	1 (1)
	-	0 (0)	2 (2)	0 (0)	2 (2)	0 (0)	0 (0)
	Neutral	0 (0)	10 (25)	0 (0)	5 (13)	0 (0)	4 (12)

introduced plants. These studies quantified success in terms of plant cover or accumulated biomass of all established plants, which usually includes species spontaneously regenerated through a natural succession process. Moreover, when plant monitoring occurs a long time after plant introduction, either by sowing or planting, success measures usually include non-introduced species. Thus, the number of species reported as positive, negative or neutrally affected may be overestimated. Furthermore, many sowing experiments include a mixture of seeds but do not report the number of species; therefore, it is even more difficult to clearly identify the number of species with positive, negative and neutral results.

4. Conclusion

In this study, we provide a global perspective of the active revegetation of mining areas without soil reconstitution based on peer-reviewed literature. Research on active revegetation of mining areas increased from the 1980s to 2017, and is highly biased towards studies in the USA, temperate climate and coal mines.

Most of the research works selected and analyzed in this review focused on treatments that improve soil conditions, with fewer articles being referred to other ecological aspects influencing plant establishment, such as biotic interactions. Furthermore, few studies tested the effects of watering and hydrogel treatments. Further research involving long-term monitoring is needed to obtain more robust outcomes on some of the studied treatments.

Although fertilization and addition of inorganic amendments have been widely used as treatments to enhance the quality and productivity of degraded soils, their effects on vegetation establishment in post-mining areas are not clear.

The results of this review suggest that organic amendment, another widely used treatment, could be a good choice to improve soil characteristics and, in turn, favor the establishment of implanted vegetation in post-mining areas. In addition to the positive effects on vegetation establishment, organic amendment is a good alternative to take advantage of urban, agricultural and forestry waste, and has a low economic and environmental cost, which could benefit the recovery of mining areas in developing countries. However, we must be cautious when generalizing about the success of these kinds of treatments, since it can vary with several factors related to the context of the intervention and thus a local assessment should always be performed. Finally, a more detailed description of the interventions may be useful to interpret results and general implications of active revegetation of mining areas. Therefore, special attention should be paid to these issues in future articles evaluating treatments to improve the active revegetation of mining areas.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

Data will be made available on request.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

Supplementary content related to this article has been published online at https://doi.org/10.1016/j.heliyon.2022.e09179.

Acknowledgements

The authors thank the colleagues M. Lucrecia Herrero and Tatiana A. Valfré-Giorello for their help in the first bibliographic search and Jorgelina Brasca for improving the English style.

References

Abella, S.R., Chiquoine, L.P., Newton, A.C., Vanier, C.H., 2015. Restoring a desert ecosystem using soil salvage, revegetation, and irrigation. J. Arid Environ. 115, 44–52.

Alday, J.G., Marrs, R.H., Martínez-Ruiz, C., 2010. The importance of topography and climate on short-term revegetation of coal wastes in Spain. Ecol. Eng. 36, 579–585.

Andrus, R.A., Harvey, B.J., Rodman, K.C., Hart, S.J., Veblen, T.T., 2018. Moisture availability limits subalpine tree establishment. Ecology 99, 567–575.

Angel, H.Z., Stovall, J.P., Williams, H.M., Farrish, K.W., Oswald, B.P., Young, J.L., 2018. Surface and subsurface tillage effects on mine soil properties and vegetative response. Soil Sci. Soc. Am. J. 82, 475–482.

Antonelli, P.M., Fraser, L.H., Gardner, W.C., Broersma, K., Karakatsoulis, J., Phillips, M.E., 2018. Long term carbon sequestration potential of biosolids-amended copper and molybdenum mine tailings following mine site reclamation. Ecol. Eng. 117, 38–49.

Aronson, J., Blignaut, J.N., Milton, S.J., Le Maitre, D., Esler, K.J., Limouzin, A., Fontaine, C., de Wit, M.P., Mugido, W., Prinsloo, P., van der Elst, L., Lederer, N., 2010. Are socioeconomic benefits of restoration adequately quantified? A meta-analysis of recent papers (2000-2008) in restoration ecology and 12 other scientific journals. Restor. Ecol. 18, 143–154.

Bochet, E., Tormo, J., García-Fayos, P., 2010. Native species for roadslope revegetation: selection, validation, and cost effectiveness. Restor. Ecol. 18, 656–663.

Bond, A.R., Piepenburg, K., 1990. Land reclamation after surface mining in the USSR: economic, political, and legal issues. Sov. Geogr. 31, 332–365.

Cao, X., 2007. Regulating mine land reclamation in developing countries: the case of China. Land Use Pol. 24, 472–483.

Carabassa, V., Ortiz, O., Alcañiz, J.M., 2019. Restoquarry: indicators for self-evaluation of ecological restoration in open-pit mines. Ecol. Indicat. 102, 437–445.

Cheng, L., Skousen, J.G., 2017. Comparison of international mine reclamation bonding systems with recommendations for China. Int. J. Coal Sci. Technol. 4, 67–79.

Clemente, A.S., Werner, C., Maguas, C., Cabral, M.S., Martins-Louçao, M.A., Correia, O., 2004. Restoration of a limestone quarry: effect of soil amendments on the establishment of native mediterranean sclerophyllous shrubs. Restor. Ecol. 12, 20–28.

Copeland, S.M., Munson, S.M., Pilliod, D.S., Welty, J.L., Bradford, J.B., Butterfield, B.J., 2018. Long-term trends in restoration and associated land treatments in the southwestern. Restor. Ecol. 26, 311–322.

Darmody, R.G., Daniels, W.L., Marlin, J.C., Cremeens, D.L., 2009. Topsoil: what is it and who cares? J. Am. Soc. Min. Reclam. 235–269.

Di Carlo, E., Chen, C.R., Haynes, R.J., Phillips, I.R., Courtney, R., 2019. Soil quality and vegetation performance indicators for sustainable rehabilitation of bauxite residue disposal areas: a review. Soil Res. 57, 419–446.

Espigares, T., Moreno-de Las Heras, M., Nicolau, J.M., 2011. Performance of vegetation in reclaimed slopes affected by soil erosion. Restor. Ecol. 19, 35–44.

Evans, D.M., Zipper, C.E., Burger, J.A., Strahm, B.D., Villamagna, A.M., 2013. Reforestation practice for enhancement of ecosystem services on a compacted surface mine: path toward ecosystem recovery. Ecol. Eng. 51, 16–23.

Faizuldayeva, Z., 2016. A comparative study of regulatory approaches to mine closure with a special emphasis on the current situation in the former Soviet Union. In: Proceedings of the 11th International Conference on Mine Closure, pp. 355–367.

Falk, D.A., Palmer, M.A., Zedler, J.B., 2016. Foundations of Restoration Ecology. Island Pre, Washington, DC USA.

Farthing, T.S., Muir, J.P., Falk, A.D., Murray, D., 2018. Efficacy of seven invasive-Bermudagrass removal strategies in three Texas ecoregions. Ecol. Restor. 36, 306–314.

Favero-Longo, S.E., Matteucci, E., Siniscalco, C., 2009. Plant colonization limits dispersion in the air of asbestos fibers in an abandoned asbestos mine. NE Nat 16, 163–177.

Foxcroft, L.C., Pyšek, P., Richardson, D.M., Genovesi, P., MacFadyen, S., 2017. Plant invasion science in protected areas: progress and priorities. Biol. Invasions 19, 1353–1378.

Frouz, J., 2021. Soil recovery and reclamation of mined lands. In: Soils and Landscape Restoration. INC, pp. 161–191.

Frouz, J., Vobořilová, V., Janoušová, I., Kadochová, Š., Matějíček, L., 2015. Spontaneous establishment of late successional tree species English oak (*Quercus robur*) and european beech (*Fagus sylvatica*) at reclaimed alder plantation and unreclaimed post mining sites. Ecol. Eng. 77, 1–8.

Fuentes, D., Disante, K.B., Valdecantos, A., Cortina, J., Ramón Vallejo, V., 2007. Response of *Pinus halepensis* Mill. seedlings to biosolids enriched with Cu, Ni and Zn in three Mediterranean forest soils. Environ. Pollut. 145, 316–323.

Fuentes, D., Valdecantos, A., Llovet, J., Cortina, J., Vallejo, V.R., 2010. Fine-tuning of sewage sludge application to promote the establishment of *Pinus halepensis* seedlings. Ecol. Eng. 36, 1213–1221.

Gastauer, M., Silva, J.R., Caldeira Junior, C.F., Ramos, S.J., Souza Filho, P.W.M., Furtini Neto, A.E., Siqueira, J.O., 2018. Mine land rehabilitation: modern ecological approaches for more sustainable mining. J. Clean. Prod. 172, 1409–1422.

Gómez-Aparicio, L., 2009. The role of plant interactions in the restoration of degraded ecosystems: a meta-analysis across life-forms and ecosystems. J. Ecol. 97, 1202–1214.

Grant, C., Koch, J., 2007. Decommissioning Western Australia's First Bauxite Mine: Co-evolving vegetation restoration techniques and targets. Ecol. Manag. Restor. 8, 92–105.

Hall, S., Barton, C., Baskin, C., 2010. Topsoil seed bank of an oak hickory forest in eastern Kentucky as a restoration tool on surface mines. Restor. Ecol. 18, 834–842.

Harrington, R.A., Fownes, J.H., Vitousek, P.M., 2001. Production and resource use efficiencies in N- and P-limited tropical forests: a comparison of responses to long-term fertilization. Ecosystems 4, 646–657.

Hernandez-Santin, L., Erskine, P.D., Bartolo, R.E., 2019. A review of revegetation at mine sites in the Alligator Rivers Region, Northern Territory, and the development of a state and transition model for ecological restoration at Ranger uranium mine. J. Clean. Prod. 246, 119079.

Herrick, J.E., Schuman, G.E., Rango, A., 2006. Monitoring ecological processes for restoration projects. J. Nat. Conserv. 14, 161–171.

Holl, K.D., Aide, T.M., 2011. When and where to actively restore ecosystems? For. Ecol. Manage. 261, 1558–1563.

Hou, J., Nan, Z., Baskin, C., Chen, T., 2021. Effect of seed size and fungicide on germination and survival of buried seeds of two grassland species on the Loess Plateau, China. Acta Oecol. 110, 103716.

Hu, Z., 2014. Legislation, Technology and Practice of Mine Land Reclamation, Legislation, Technology and Practice of Mine Land Reclamation. CRC Press, London.

Jabloun, M., Schelde, K., Tao, F., Olesen, J.E., 2015. Effect of temperature and precipitation on nitrate leaching from organic cereal cropping systems in Denmark. Eur. J. Agron. 62, 55–64.

Josa, R., Jorba, M., Vallejo, V.R., 2012. Opencast mine restoration in a Mediterranean semi-arid environment: failure of some common practices. Ecol. Eng. 42, 183–191.

Kesler, S.E., 2007. Mineral supply and demand into the 21st century. In: Briskey, J.A., Schulz, K.J. (Eds.), Proceedings for a Workshop on Deposit Modeling, Mineral Resource Assessment, and Their Role in Sustainable Development, Circular 1294. US Geological Survey Circular, pp. 55–62.

Kirmer, A., Tischew, S., Ozinga, W.A., von Lampe, M., Baasch, A., van Groenendael, J.M., 2008. Importance of regional species pools and functional traits in colonization processes: predicting re-colonization after large-scale destruction of ecosystems. J. Appl. Ecol. 45, 1523–1530.

Kirmer, A., Baasch, A., Tischew, S., 2012. Sowing of low and high diversity seed mixtures in ecological restoration of surface mined-land. Appl. Veg. Sci. 15, 198–207.

Köppen, W., 1936. Das geographische system der Klimate. In: Köppen, W., Geiger, R. (Eds.), Handbuch Der Klimatologie. Gebrüder Bornträger, Berlin, p. 44.

Kumari, S., Maiti, S.K., 2019. Reclamation of coalmine spoils with topsoil, grass, and legume: a case study from India. Environ. Earth Sci. 78, 429.

Lei, K., Pan, H., Lin, C., 2016. A landscape approach towards ecological restoration and sustainable development of mining areas. Ecol. Eng. 90, 320–325.

Li, X., Niu, J., Xie, B., 2014. The effect of leaf litter cover on surface runoff and soil erosion in Northern China. PLoS One 9, e107789.

Li, Z., Schneider, R.L., Morreale, S.J., Xie, Y., Li, J., Li, C., Ni, X., 2019. Using woody organic matter amendments to increase water availability and jump-start soil restoration of desertified grassland soils of Ningxia, China. Land Degrad. Dev. 30, 1313–1324.

Lima, A.T., Mitchell, K., O'Connell, D.W., Verhoeven, J., Van Cappellen, P., 2016. The legacy of surface mining: remediation, restoration, reclamation and rehabilitation. Environ. Sci. Pol. 66, 227–233.

Macdonald, S.E., Landhäusser, S.M., Skousen, J., Franklin, J., Frouz, J., Hall, S., Jacobs, D.F., Quideau, S., 2015. Forest restoration following surface mining disturbance: challenges and solutions. New Times 46, 703–732.

Martínez-Ruiz, C., Fernández-Santos, B., Putwain, P.D., Fernández-Gómez, M.J., 2007. Natural and man-induced revegetation on mining wastes: changes in the floristic composition during early succession. Ecol. Eng. 30, 286–294.

Masoumi, I., Naraghi, S., Rashidi-nejad, F., Masoumi, S., 2014. Application of fuzzy multi-attribute decision-making to select and to rank the post-mining land-use. Environ. Earth Sci. 72, 221–231.

Matias, S.R., Pagano, M.C., Muzzi, F.C., Oliveira, C.A., Carneiro, A.A., Horta, S.N., Scotti, M.R., 2009. Effect of rhizobia, mycorrhizal fungi and phosphate-solubilizing microorganisms in the rhizosphere of native plants used to recover an iron ore area in Brazil. Eur. J. Soil Biol. 45, 259–266.

Mborah, C., Bansah, K.J., Boateng, M.K., 2016. Evaluating alternate post-mining land-uses: a review. Environ. Pollut. 5, 14.

Milder, A.I., Fernández-Santos, B., Martínez-Ruiz, C., 2013. Colonization patterns of woody species on lands mined for coal in Spain: preliminary insights for forest expansion. Land Degrad. Dev. 24, 39–46.

Navarro Ramos, S.E., Renison, D., Becerra, A.G., 2018. La inoculación con hongos micorrícicos arbusculares promueve el crecimiento de plantines de *Kageneckia lanceolata* (Rosaceae). Bol. la Soc. Argentina Bot. 53, 161–167.

Novianti, V., Marrs, R.H., Choesin, D.N., Iskandar, D.T., Suprayogo, D., 2018. Natural regeneration on land degraded by coal mining in a tropical climate: lessons for ecological restoration from Indonesia. Land Degrad. Dev. 29, 4050–4060.

Oliet, J.a., Puértolas, J., Planelles, R., Jacobs, D.F., 2013. Nutrient loading of forest tree seedlings to promote stress resistance and field performance: a Mediterranean perspective. New Times 44, 649–669.

Oliveira, G., Clemente, A., Nunes, A., Correia, O., 2013. Limitations to recruitment of native species in hydroseeding mixtures. Ecol. Eng. 57, 18–26.

Ortiz, O., Ojeda, G., Espelta, J.M., Alcañiz, J.M., 2012. Improving substrate fertility to enhance growth and reproductive ability of a *Pinus halepensis* Mill. afforestation in a restored limestone quarry. New Times 43, 365–381.

Ottavini, D., Pannacci, E., Onofri, A., Tei, F., Jensen, P.K., 2019. Effects of light, temperature, and soil depth on the germination and emergence of *Conyza canadensis* (L.) Cronq. Agronomy 9, 1–15.

Passaretti, R.A., Pilon, N.A.L., Durigan, G., 2020. Weed control, large seeds and deep roots: drivers of success in direct seeding for savanna restoration. Appl. Veg. Sci. 23, 406–416.

Pedrini, S., Gibson-Roy, P., Trivedi, C., Gálvez-Ramírez, C., Hardwick, K., Shaw, N., Frischie, S., Laverack, G., Dixon, K., 2020. Collection and production of native seeds for ecological restoration. Restor. Ecol. 28, S228–S238.

Pickering, C., Byrne, J., 2014. The benefits of publishing systematic quantitative literature reviews for PhD candidates and other early-career researchers. High Educ. Res. Dev. 33, 534–548.

Plamping, K., Haigh, M., Reed, H., Woodruffe, P., Fitzpatrick, S., Farrugia, F., D'Aucourt, M., Flege, A., Sawyer, S., Panhuis, W., Wilding, G., Cullis, M., Powell, S., 2016. Effects of initial planting method on the performance of mixed plantings of alder and oak on compacted opencast coal-spoils, Wales: 10-year results. Int. J. Min. Reclamat. Environ. 31, 286–300.

Ploughe, L.W., Akin-Fajiye, M., Gagnon, A., Gardner, W.C., Fraser, L.H., 2021. Revegetation of degraded ecosystems into grasslands using biosolids as an organic amendment: a meta-analysis. Appl. Veg. Sci. 24, 1–15.

Portsmuth, A., Niinemets, Ü., 2007. Structural and physiological plasticity in response to light and nutrients in five temperate deciduous woody species of contrasting shade tolerance. Funct. Ecol. 21, 61–77.

Prach, K., del Moral, R., 2015. Passive restoration is often quite effective: response to Zahawi et al. Restor. Ecol. 23, 344–346, 2014.

Prach, K., Walker, L.R., 2019. Differences between primary and secondary plant succession among biomes of the world. J. Ecol. 107, 510–516.

Prach, K., Šebelíková, L., Řehounková, K., del Moral, R., 2020. Possibilities and limitations of passive restoration of heavily disturbed sites. Landsc. Res. 45, 247–253.

Pueyo, Y., Alados, C.L., 2007. Effects of fragmentation, abiotic factors and land use on vegetation recovery in a semi-arid Mediterranean area. Basic Appl. Ecol. 8, 158–170.

Reid, N.B., Naeth, M.A., 2005. Establishment of a vegetation cover on tundra kimberlite mine tailings: 2. A field study. Restor. Ecol. 13, 594–601.

Schiffers, K., Tielbörger, K., 2006. Ontogenetic shifts in interactions among annual plants. J. Ecol. 94, 336–341.

Šebelíková, L., Řehounková, K., Prach, K., 2016. Spontaneous revegetation vs. forestry reclamation in post-mining sand pits. Environ. Sci. Pollut. Res. 23, 13598–13605.

SER, 2004. The SER International Primer on Ecological Restoration. Society for Ecological Restoration International Science & Policy Working Group. https://www.ser.org.

Sheoran, V., Sheoran, A.S., Poonia, P., 2010. Soil reclamation of abandoned mine land by revegetation: a review. Int. J. Soil Sediment Water 3, 1–21.

Shriver, R.K., Andrews, C.M., Pilliod, D.S., Arkle, R.S., Welty, J.L., Germino, M.J., Duniway, M.C., Pyke, D.A., Bradford, J.B., 2018. Adapting management to a changing world: warm temperatures, dry soil, and interannual variability limit restoration success of a dominant woody shrub in temperate drylands. Glob. Change Biol. 24, 4972–4982.

Skousen, J., Zipper, C.E., 2014. Post-mining policies and practices in the Eastern USA coal region. Int. J. Coal Sci. Technol. 1, 135–151.

Soliveres, S., Monerris, J., Cortina, J., 2012. Irrigation, organic fertilization and species successional stage modulate the response of woody seedlings to herbaceous competition in a semi-arid quarry restoration. Appl. Veg. Sci. 15, 175–186.

Spargo, A., Doley, D., 2016. Selective coal mine overburden treatment with topsoil and compost to optimise pasture or native vegetation establishment. J. Environ. Manag. 182, 342–350.

Torres, R.C., Renison, D., 2015. Effects of vegetation and herbivores on regeneration of two tree species in a seasonally dry forest. J. Arid Environ. 121, 59–66.

Torroba-Balmori, P., Zaldívar, P., Alday, J.G., Fernández-Santos, B., Martínez-Ruiz, C., 2015. Recovering *Quercus* species on reclaimed coal wastes using native shrubs as restoration nurse plants. Ecol. Eng. 77, 146–153.

Trepanier, K.E., Pinno, B.D., Errington, R.C., 2021. Dominant drivers of plant community assembly vary by soil type and time in reclaimed forests. Plant Ecol. 222, 159–171.

U.S. Energy Information Administration, 2019. n.d, Total energy production 2017 [WWW Document]. URL. https://www.eia.gov/international/rankings/country/. (Accessed 17 February 2020).

UNCTAD, 2020. Digital Economy Growth and mineral Resources. Implications for Developing Countries. United Nations Conference on Trade and Development. https://www.unctad.org.

USGS, 2019. U.S. Geological survey. Miner. Commod. Summ. 2019. [WWW Document]. URL https://www.usgs.gov/centers/nmic/mineral-commodity-summaries. (Accessed 3 February 2020).

Van Andel, J., 2005. Species interactions structuring plant communities. In: Van der Maare, E., Franklin, J. (Eds.), Vegetation Ecology. Blackwell Publishing, Oxford, pp. 238–264, 2005.

Wortley, L., Hero, J.M., Howes, M., 2013. Evaluating ecological restoration success: a review of the literature. Restor. Ecol. 21, 537–543.

Zettl, J.D., Barbour, S.L., Huang, M., Si, B.C., Leskiw, L.A., 2011. Influence of textural layering on field capacity of coarse soils. Can. J. Soil Sci. 91, 133–147.