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Biology-Ecology

Recovery processes in areas affected by mining: a sciencIometric review

Processos de recuperação em áreas afetadas por mineração: uma revisão cienciométrica

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ABSTRACT

A major challenge in using recovery techniques, for the different natural ecosystems affected by mining, is a mutual relationship between the habitat and its biota response. This study aimed to do a review to identify the number of publications, which countries are publishing more and which recovery techniques and taxonomic group are used in mining areas globally have contributed to the maintenance or recovery of the environment. We reviewed the literature on recovery in mining areas worldwide, between 1994 and 2016, using the Web of Science online database. We identified 9,000 publications, after the selection procedures, we analyzed the 467 remaining manuscripts. Of these, 34.26% were published between 1994 and 2004, and 65.74% between 2006 and 2016. The countries that contributed the most were the USA with 16.45%, Australia with 13.56% and China with 8.66%. Brazil contributed 6.9% of the publications. The recovery techniques using vegetation were the most reported in the literature and most used. The taxonomic group of terrestrial plants was the most cited and most used in the recovery of degraded areas. We found various techniques for recovering degraded areas can be established, but most of them did not show proper monitoring and without this the recovery processes may not achieve their objectives and studies that test the effect size of these recovery methods are still necessary.

Keywords: Ore; Revegetation; Remediation; Land use; Landscape

RESUMO

Um grande desafio no uso de técnicas de recuperação, para os diferentes ecossistemas naturais afetados pela mineração, é uma relação conjunta entre a resposta do habitat e a biota. O objetivo deste estudo foi realizar uma revisão para identificar o número de publicações; quais países estão publicando mais; quais técnicas de recuperação; e grupo taxonômico são mais usados nas áreas de mineração e que contribuíram para a manutenção ou recuperação do meio ambiente. Revisamos a literatura sobre recuperação em áreas de mineração em todo o mundo, entre 1994 e 2016, usando o banco de dados on-line da *Web of Science*. Foram identificadas 9.000 publicações; após os procedimentos de seleção, foram analisados 467 manuscritos restantes. Desses, 34,26% foram publicados entre 1994 e 2004 e 65,74% entre 2006 e 2016. Os países que mais contribuíram foram os EUA com 16,45%, a Austrália com 13,56% e a China com 8,66%. O Brasil contribuiu com 6,9% das publicações. As técnicas de recuperação com vegetação foram as mais relatadas na literatura e as mais utilizadas. O grupo taxonômico de plantas terrestres foi o mais citado e mais utilizado na recuperação de áreas degradadas. Descobrimos que várias técnicas para recuperar áreas degradadas podem ser estabelecidas, mas a maioria não mostrou monitoramento adequado e, sem isso, os processos de recuperação podem não atingir seus objetivos e estudos que testam os tamanhos de efeitos dessas técnicas ainda são necessários.

Palavras-chave: Minério; Revegetação; Remediação; Uso do solo; Paisagem

1 INTRODUCTION

Mining activities contribute to global socio-economic development but also contribute to increased pressure on natural systems (RAKOTONDRABE *et al*., 2018). Finding appropriate recovery techniques compatible with the climatic dynamics of the landscape and the biodiversity of each type of environment has become a major challenge (DA CRUZ *et al.,* 2020). In addition, there is growing concern about the development of mining activities, as this anthropic activity involves the removal of large amounts of soil and alteration of the natural landscape (SCHUELER *et al.,* 2011; ROSS *et al.,* 2016). The main environmental modifications involve vegetation suppression, increased erosion, loss of soil nutrients, deposition of chemical wastes, and water contamination that may compromise the entire drainage system of a basin (BROSSE *et al.,* 2011; MENSAH *et al.,* 2015; SONTER *et al.,* 2017). Such changes are not restricted to a single part of an ecosystem, but can affect both aquatic and terrestrial environments with loss of biodiversity and ecosystem services (SALOMONS, 1995; SALA *et al.,* 2000; KRAUSS *et al.,* 2010; ATTUQUAYEFIO *et al.,* 2017). For example, in the eastern Amazon, mining activities are responsible for the deforestation of 100,000 ha and the prospect of continued growth for the next few years is causing concern about the preservation of the natural heritage for future generations (CABALLERO ESPEJO *et al.,* 2018).

In most countries, some laws require mining companies to adopt strategies to recover areas that have been mined or affected by mining (e.g., USA, 1977; BRASIL, 1989; WA, 2015), to reconstitute their resilience. Recovery of these areas involves revegetation and monitoring of bioindicators to facilitate post-impact management and to verify if the recovery target is being reached (WORTLEY *et al.,* 2013). However, these plans are often non-existent, forgotten after the exploration, or do not reach the targets for successful recovery (HOLL, 2002; RUIZ-JAEN, AIDE, 2005). This success depends on the type of soil, the species used for reforestation (and their adaptation), regional climate and planting techniques, among many other factors (ALMEIDA *et al.,* 2019). In addition, the supervision or monitoring of these activities is not always been satisfactory. Previous studies show the importance of applying specific recovery techniques to improve forest recovery and methodological alignment (PARROTTA, KNOWLES, 2001; SANTERO, HENDRY, 2016; MARTINS *et al.,* 2020). Despite the need for effective recovery techniques, the poor systematic management has made 'trial-and-error' practices the most common type of recovery method. However, monitoring these techniques provides important information that can be used to optimize recovery procedures (GASTAUER *et al.,* 2018). In this way, collecting information about the environment and continuously evaluating current and historical mining impacts can help in decision making for the recovery and monitoring processes used. The right decision could prevent undesirable impacts and reduce economic damage to recovering degraded areas (SALOMONS, 1995).

The present study is a literature review on the ecosystem recovery of mining areas world-wide. Our aim was to identify the principal research themes and any existing gaps in recovery techniques of mining areas world-wide. The main issues analyzed in the present study were: (i) what are the temporal and spatial trends in the publication of recovery articles from environments impacted by mining activities?; (ii) which country contributes the most with scientific publications about the type of recovery technique?; (iii) what are the most commonly used recovery techniques in areas affected by mining activities?; (iv) is there a trend in these techniques, or are they variable according to ore types? and (v) which taxonomic groups have been most used to evaluate recovery techniques?

2 MATERIALS AND METHODS

We conducted a literature search of scientific articles published in the last 22 years (1994-2016), with 1994 being the year when computerization of periodicals, which published studies of mining areas, took place. We used the Web of Science (https://www.webofknowledge.com/) online database. We searched for the following words as keywords in titles: Impact* OR restoration OR rehabilitation OR recovery OR revegetation OR “environmental impact*” OR succession, and mining OR mine OR “industrial mineral”, and we excluded the words: stone* OR sediment* OR microbial OR “chemical”.

First, from the total number of articles, we only selected the articles discussing mining activities, the keyword bibliometric data were used to generate a network map with an overview of the relationship and use of terms in mining works published worldwide. For that, we used VOSviewer software (ECK, WALTMAN, 2019).

In a second selection, we only used studies about cover restoration processes in mining areas globally. From each manuscript selected, we catalogued: (i) scientific articles, (ii) year of publication and (iii) journal name. We extracted the following information from the selected material: (iv) the type of ore being mined, the location where the mining activity took place – (v) continent and (vi) country, (vii) the environment (aquatic, terrestrial or both), (viii) duration of exploitation and (ix) if the study was on impact monitoring or recovery research. We also collected information regarding: (x) indicators of impact (chemical, physical or biological), (xi) indicators of recovery (chemical, physical or biological), (xii) the biological group, (xiii) the consequences of the mining activity (impacts on soil, water chemistry, etc.), (xiv) the type of recovery technique that was applied, and (xv) the problems reported for each recovery technique.

After that, we calculated descriptive statistics to assess trends and approaches in the literature (e.g., most frequent journals, citations number, environments, continents, countries, anthropogenic factors, etc.) and global trends in the environments studied. We grouped the recovery processes based on a larger scale of their involvement in the recovery process. For example, we classified processes involving plants as “procedures with vegetation”; we grouped processes involving extraction of toxicity from the environment in “remediation”; water and soil were grouped in “hydro-geo procedures”, and processes that described educational and legislative actions were inserted in “socio-environmental procedures”.

Manuscripts regarding recovery in areas mined for two to five types of ore were separated and considered as one lot each. The papers that referred to the mining of several types of metals (> 5 ores in each paper) were classified as metals and were not separated according to the type of metal. To verify if there was any tendency or variation in the techniques used, in relation to the types of ore explored, we selected only the ore with the highest occurrence in the studies and excluded ores that had a low occurrence (<10) in the literature. The manuscripts that did not specify the type of ore explored in the study areas were grouped in “not specified”.

We classified the taxonomic groups according to the biological division of the kingdoms. We subdivided the animal kingdom into two groups: vertebrate and invertebrate. We then separate the taxa into two groups according to their habitat (aquatic, terrestrial, or both). In the plant kingdom, we grouped the plants into groups according to their habitat (aquatic, terrestrial or both). We grouped the other taxa in the Fungi (fungi), Monera (bacteria), and Protista (algae) kingdoms.

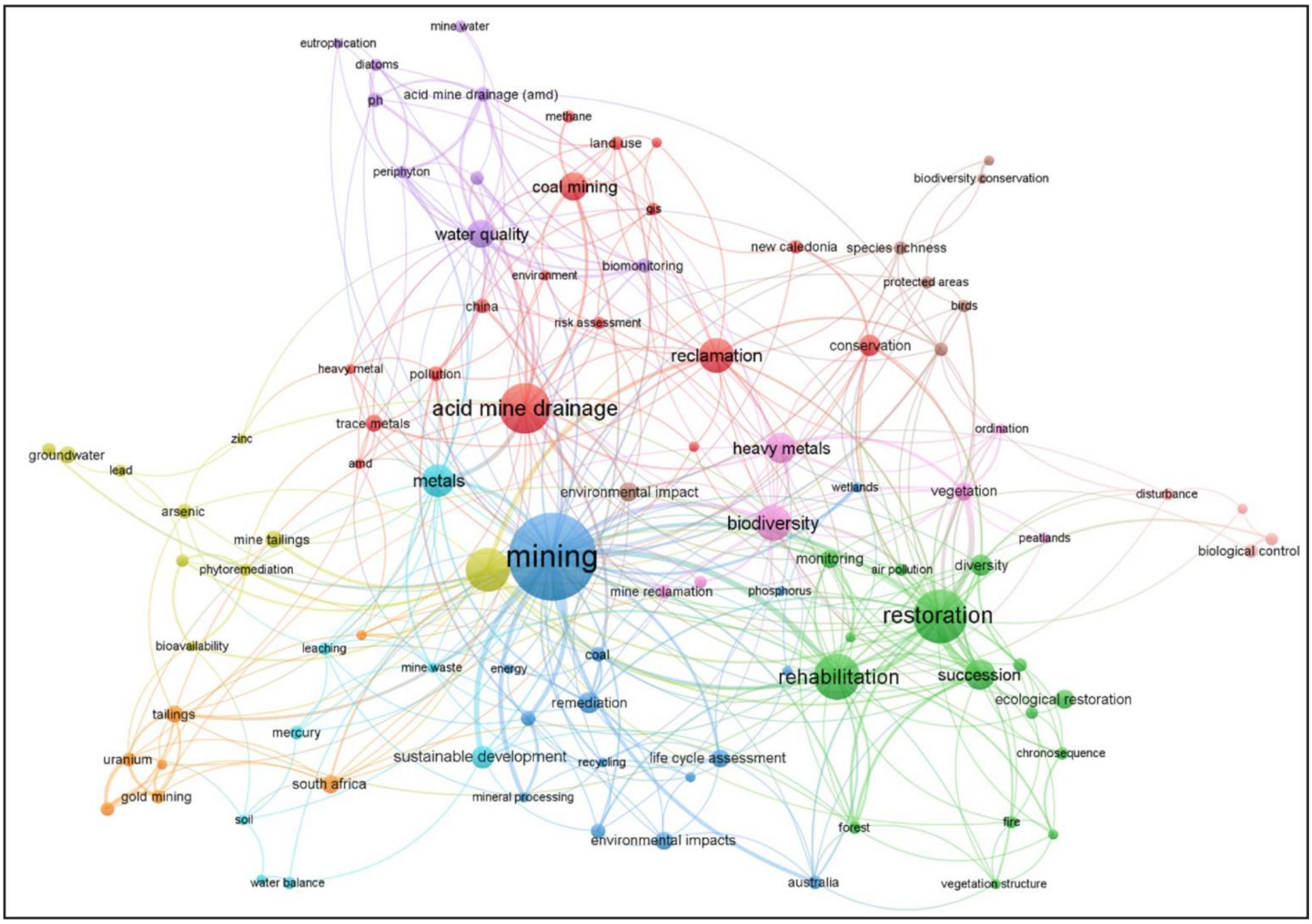
However, when we found different taxonomic groups being evaluated in the manuscript (e.g., vertebrates and plants), these were classified as multi-taxa. Thus, the taxa were classified as a terrestrial plants, aquatic plants, terrestrial and aquatic plants, terrestrial invertebrate, aquatic invertebrate, terrestrial vertebrate, aquatic vertebrate, terrestrial and aquatic vertebrate, Fungi, Monera, Protista, and multi-taxa. With the most used taxa registered, we performed a non-metric multidimensional scaling – NMDS to see if there is a difference between the distribution of taxonomic groups and recovery techniques in mining areas. This analysis assessed the distortion between the similarity matrix and the clustering pattern revealed in the graphic representation, providing a reliability measure of the analysis for results interpretation (CLARKE, 1993).

3 RESULTS AND DISCUSSION

3.1 Overview

We identified a total of 9,000 manuscripts, from 1994 to 2016, 882 studies that focused its research in mining areas were selected. The network visualization shows the interactions of keywords and the formation of some clusters (Figure 1). In this graph, circle size represents the number of articles found with the keyword and the distance between these circles and the width of the line represents the strength of the relationship. The groups formed by different colors represent stronger relations with each other. It is possible to identify the main keywords found were mining, restoration, rehabilitation and acid mine drainage, with the stronger relationships only between the first three. This pattern shows that it is common to find articles relating restoration and rehabilitation to mining processes.

Figure 1 – Bibliometric map with the keywords used in the articles published on mining processes

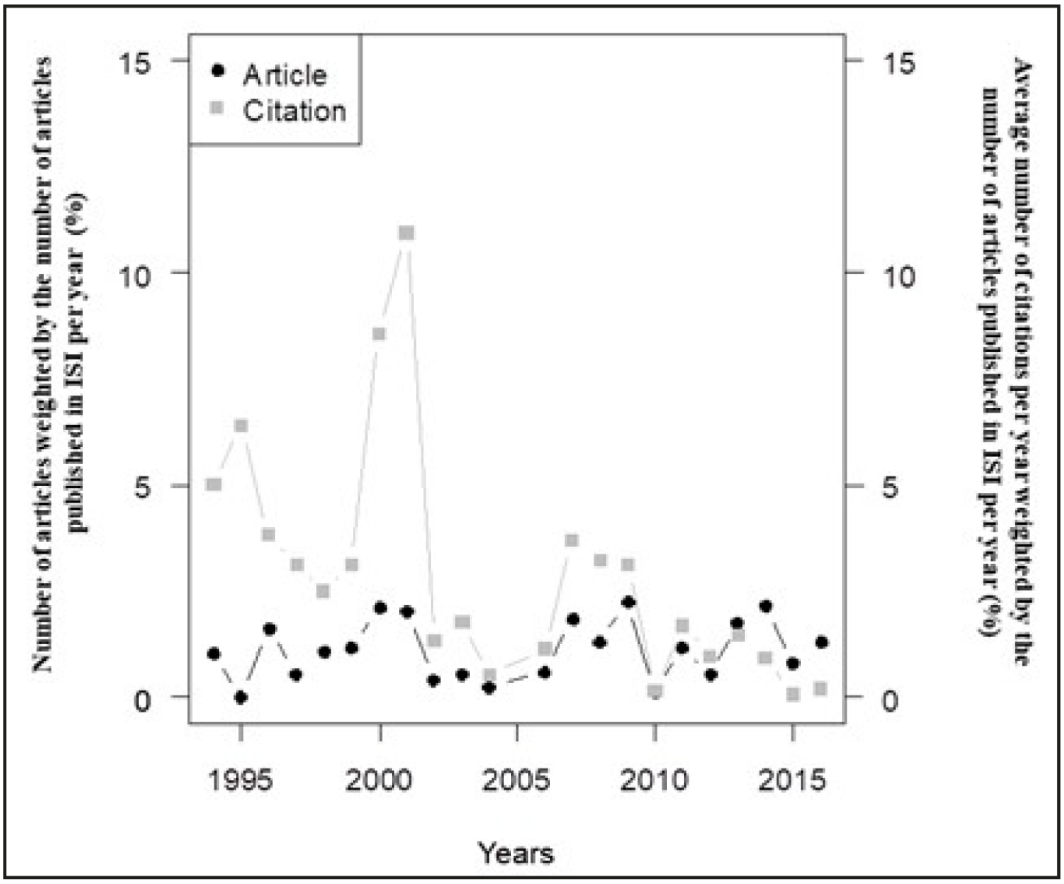


3.2 Temporal and spatial trends in the publication of manuscripts on recovery in mining areas

After the selection procedure of cover restoration processes in mining areas globally, we read 467 manuscripts. In 467 manuscripts, 160 (34.26%) were published between 1994 and 2004, and 307 (65.74%) between 2006 and 2016. The year 2014 had the highest number of publications, with 52 (11.13%) published (Figure 2) and we found no publications regarding the topics researched in 2005. In this result, the increased number of articles with this focus could be explained by two points, first because the number of articles published increased during this time (independent of the study area) and this pattern is found in others studies

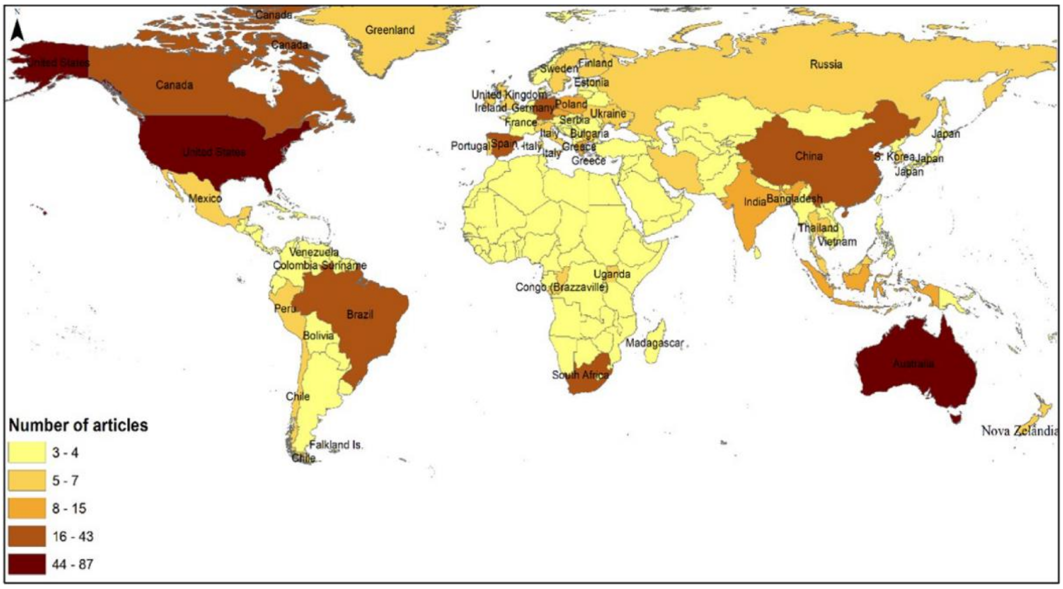
(LUIZA-ANDRADE *et al.,* 2017, COSTA *et al.,* 2020, PEREIRA *et al.,* 2020b), but also for the increasing number of mining areas which consequently increased studies that are interested in aiding to recover deforested areas (SONTER, BARRETT, SOARES-FILHO, 2014; MARTINS *et al.,* 2020; SONTER *et al.,* 2017).

Figure 2 – Temporal variation involving the number of recovery work citations in mining areas and the number of scientific publications between the years 1994 and 2016



Seventy-six countries contributed to research on the advancement of recovery techniques in mining areas. On a continental scale (Figure 3), the countries that most contributed were the United States of America with 131 (16.45%), Australia with 108 (13.56%) and China with 69 (8.66%). While Brazil contributed to 55 publications (6.90%), followed by Canada with 51 (6.40%), Spain with 50 (6.28%) and South Africa with 44 (5.52%).

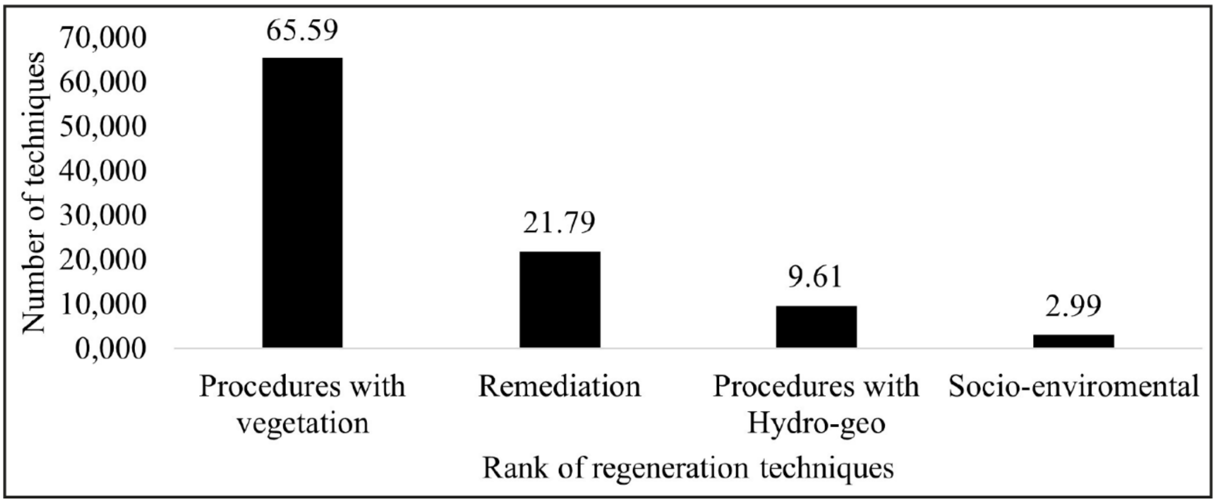
Figure 3 – Distribution of scientific literature published by country involving the processes of recovery in mining areas between 1994 and 2016



3.3 Most used recovery techniques, with their variations, in relation to ore types

We found 84 processes related to recovery techniques reported in the articles. We classified the recovery techniques into four groups' procedures: vegetation, remediation, hydro-geo and socio-environmental (Figure 4). Thus, there were 307 publications from 45 countries that involved the use of plants in recovery techniques for mining areas (procedures with vegetation), corresponding to 65.6% of the 467 publications on recovery. Second, the techniques that involved remediation processes were used in 28 countries and 102 publications, corresponding to 21.8% of publications on recovery. With 45 publications distributed in 17 countries, the hydro-geo procedures accounted for 9.61% of the survey. Whereas socio-environmental approaches, with 14 publications distributed in nine countries, accounting for 2.99% of the research. In the 22 years of publications on the effects of mining and its main recovery techniques, it is relevant and interesting to point out that only Australian and Brazilian mines have featured in publications covering conservation policy and environmental education. For Brazil, this is in accordance to the public policies regarding environmental protection that we passed in the 2000s (DRUMMOND, BARROS-PLATIAU, 2006; NEPSTAD *et al.,* 2009), but unfortunately it has changed now (PEREIRA *et al.,* 2020a).

Figure 4 – Percentage of recovery techniques involving 467 articles published between 1994 and 2016 across the world



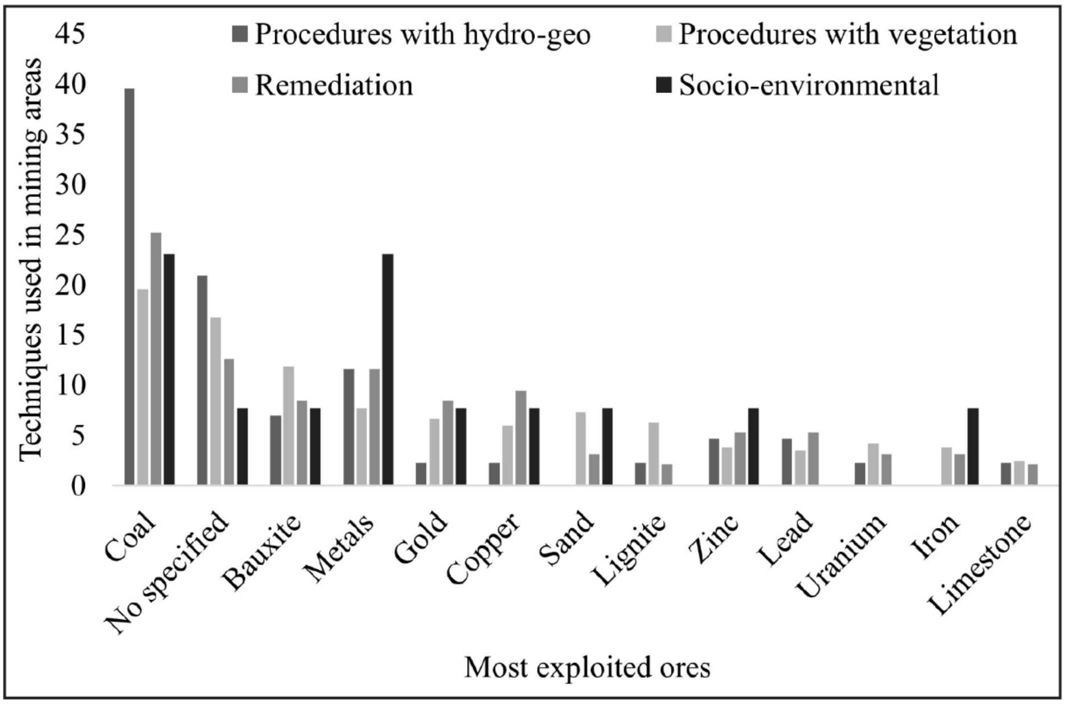
The main recovery techniques used were revegetation and remediation, and most involved vegetation and soil stabilization techniques, which include soil compaction, granulometric correction and/or the addition of chemical stabilizer. The success of the recovery of the degraded area is also related to the time that is given for the edaphic and biological changes to occur (MUNSHOWER, 2018). Since in addition to altering the soil, there must be enough time for vegetation to establish itself again. In this context, another technique that also looks promising involves the transfer of fertile soil to degraded areas, allowing faster recovery of vegetation in terms of species composition, similarity and richness (BURKE, 2008; BULOT *et al.,* 2014).

The success of recovery techniques also depends on soil moisture and nutrient availability (LI, LIBER, 2018), and may be key factors in the relationship of these two procedures (vegetation and hydro-geo) in post-mining-disturbance recovery. For example, CHAN *et al.* (2014) observed that during approximately 15 years of soil recovery, the recovery of the original vegetation was successful, with species that were planted being progressively replaced by ruderal species. Based on this, besides the recovery of the physical environment, techniques involving the revegetation of the area contribute to the increase in the dispersion of limited seeds during natural recovery processes and, consequently, help late-growth species to colonize (PARROTTA, KNOWLES, 2001). These joint practices, associated with a replacement of the topsoil and composting techniques are essential for rapid soil recovery (FERREIRO *et al.,* 2019), further contribute to an increase in biodiversity (PARROTTA, KNOWLES, 2001) in each place.

The success of recovery using vegetation also depends on the success of colonization by pioneer species (CRAW *et al.,* 2007; MUNSHOWER, 2018). Once these species are able to colonize the environment, act as phyto-stabilizers, because of their high tolerances to environmental disturbances, and are able to stabilize the degraded soil, reduce their temperature, prevent erosion and increase organic matter in the soil, for example, adding the nutrients needed for native species to develop (MUNSHOWER, 2018). With this, these species are able, directly or indirectly, to facilitate the growth of seedlings and seedlings that can be placed subsequently (YUAN *et al.*, 2019). When carefully selected, according to local factors, local species can stabilize over the years and increase their density, resulting in a succession of annuals to perennials (BROFAS, VARELIDES, 2000).

In a total, 58 types of ores explored on all continents were cited. When we verified if there was any tendency or variation in the techniques used, in relation to the types of ores exploited (Figure 5), we noticed that the extraction of coal, corresponding to 23.42%, was the most cited ore of the 467 manuscripts evaluated. In the geotechnics, 40.47% of the published manuscripts covered areas of coal mining, however 21.43% of the papers did not specify the type of ore exploited. We observed this same pattern for the processes using vegetation: 16.4% of the total articles published did not specify the type of ore exploited, which hinders our understanding of recovery techniques used in mining areas after landscape changes.

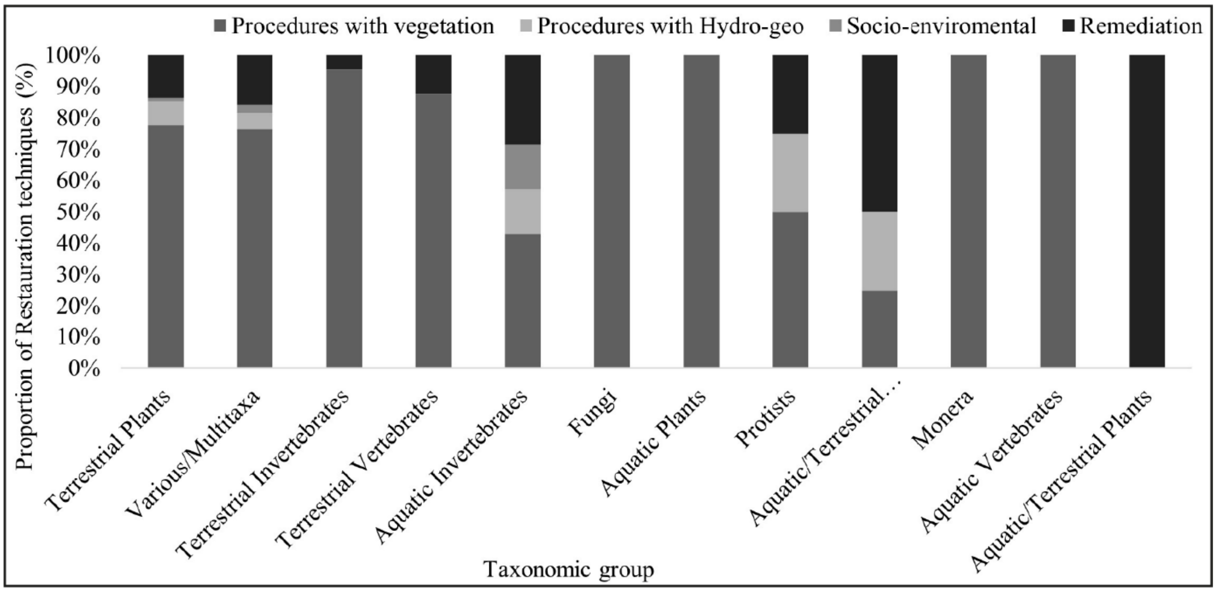
Figure 5 – Ores and techniques most cited between the years 1994-2016



3.4 Biodiversity in the evaluation of recovery techniques in mining areas

For the 467 evaluated articles, about 357 informed the taxonomic groups used as tools to evaluate recovery techniques, for which we recorded 12 taxonomic groups (Figure 6). The main taxonomic groups used in the articles were terrestrial plants (n = 256), multi-taxa (n = 38), terrestrial invertebrates (n = 22) and terrestrial vertebrates (n = 8). The terrestrial plants and multi-taxa were used to evaluate all recovery techniques that we found, with the most predominant being procedures with vegetation (n = 199 and n = 29 for terrestrial plants and multi-taxa respectively), followed by remediation processes (n = 35 and n = 6), hydro-geo (n = 19 and n = 2) and socio-environmental (n = 3 and n = 1 for each one respectively) procedures. The work using invertebrates and terrestrial vertebrates presented only two recovery techniques: procedures with vegetation (n = 21 and n = 7, respectively) and remediation (n = 1, for both). In addition, we tried to assess if the distribution of taxonomic groups was related to any recovery techniques in mining areas and the NMDS did not show the difference between them (Figure 7). Although the procedures with vegetation technique have some points that were more separated in the graph, most were overlapped with other restoration techniques, demonstrating only the procedures with vegetation have more considerable variation, but not that there are significant differences.

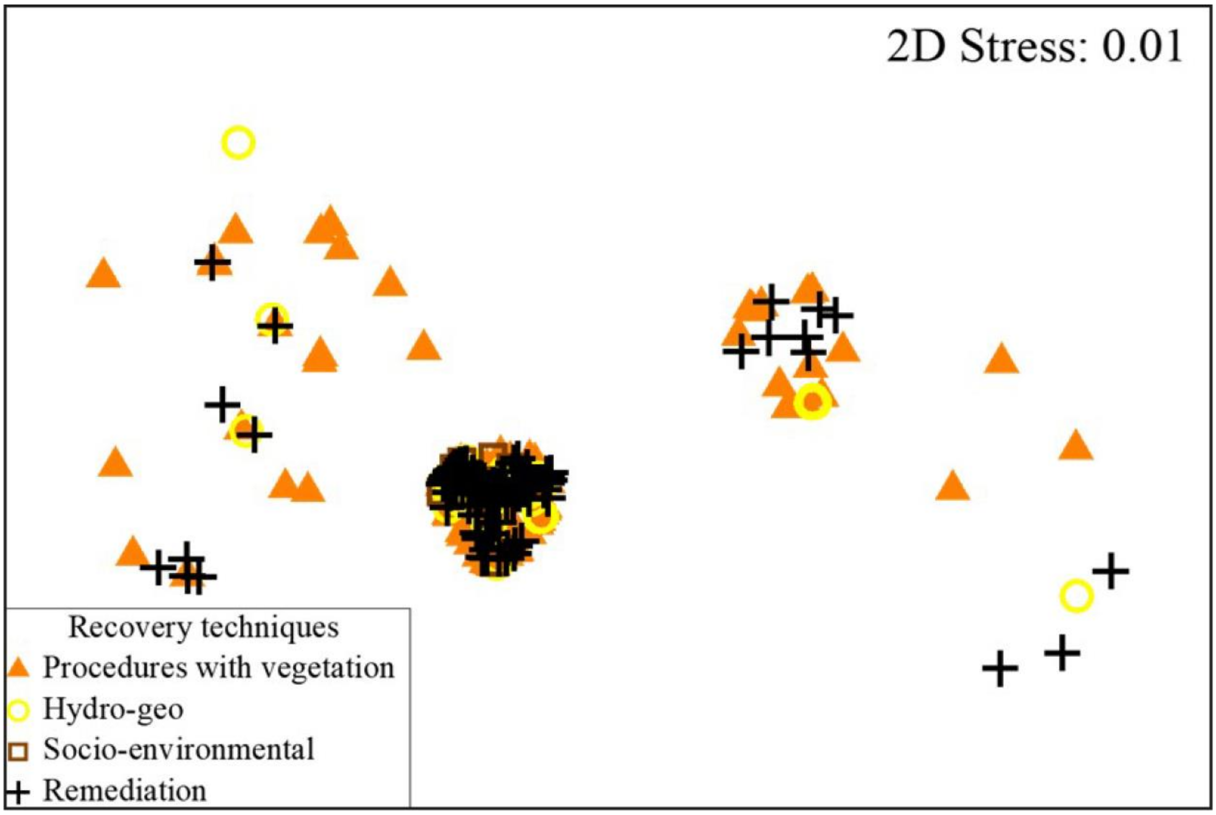
Figure 6 – Taxonomic groups used to evaluate restoration techniques



The structure of vegetation has been used in studies that evaluate ecological recovery in mining (RUIZ-JAEN, AIDE, 2005). The predominance of this taxonomic group in studies with an emphasis on recovery are related to three main points: (i) laws on ecological recovery always require vegetation structure monitoring (ALLEN, 1992), (ii) the establishment of vegetation in recovery areas should contribute to the recovery and restoration of the fauna (e.g., invertebrates, birds, and amphibians) (TOTH *et al.,* 1995; YOUNG, 2000; SUDARMADJI, HARTATI, 2016), and (iii) measures associated with vegetation structure are considered easy and quick to measure (RUIZ-JAEN, AIDE, 2005).

Other taxonomic groups, such as invertebrates and vertebrates, have also been used to evaluate the effectiveness of recovery techniques in the environment (NICHOLS, NICHOLS, 2003). However, it is also important to understand that no single taxonomic group is adequate as a “bioindicator” of recolonization of organisms in restored environments, since each group presents a unique pattern from the others (NICHOLS, NICHOLS, 2003). This justify the use of multiple taxonomic groups that we found in studies evaluating recovery techniques, together with this, studies evaluating multiple groups may also indicate ecosystem health issues, such as decomposition, pollination, bioremediation (using aquatic and terrestrial plants), biological control (like predation) and these are very important for conservation and biodiversity. In this way, monitoring the response of key species together with the recovery of ecosystem services provided by them is one of the most efficient ways to show that the restoration process was indeed effective.

Figure 7 – Non-metric Multidimensional Scaling - NMDS showing the distribution of taxonomic groups in recovery techniques: Procedures with vegetation, Hydro-geo, Socio-environmental and Remediation



4 CONCLUSION

We found that articles dealing with recovery in mining areas, in general, increased in line with the greater importance of mining in the global economy. The growth of the mining sector and environmental discussions worldwide may have been the factor that stimulated scientific studies involving the subject. The countries that contributed the most to research on the advancement of recovery techniques in mining areas were the United States of America, Australia and China with almost 40% of total publications. We also found that the most common recovery technique of mining areas worldwide are procedures with vegetation. There are few articles focused on socio-environmental development in these areas. It is important to emphasize that recovery techniques used in degraded areas aim to recover the landscape structure, function and native diversity, which explain why this recovery technique is more common. Moreover, the articles did not show a trend in the techniques used according to ore types. Terrestrial plants are the most use taxonomic group in these articles (following the most common technique). However, it is important to say that there is no relationship between taxonomic groups and the techniques. Meaning there is no preference of just one taxonomic group for each recovery technique (procedures with vegetation, hydro-geo, socio-environmental and remediation).

Finally, although it was not covered in this study, we would like to alert that it is important not only to have reforestation practices in a single moment but also to monitor these areas after a few years of extraction as this could help recovery teams achieve their aims. Because during all processes, some species can vary their responses, such as increased abundance after disturbances, and this could be a problem, especially if the area is not monitored. Unfortunately, such information is not available here or in the articles used in this review and this can be a gap for this subject. Most of the exploited areas are abandoned after mineral extraction, without proper management or monitoring, making mining effects even more pronounced and prolonged (MENSAH *et al*., 2015). For the future, to identify which studies have a temporal approach to test the technique throughout the years and research that are interested in testing the size effect of these recovery methods (for example, using meta-analysis) will be essential to measure which ones are more effective on revegetation and it will advance the knowledge about them.

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