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Review

Ecological methods and indicators for recovering and monitoring ecosystems after mining: A global literature review

Walmer Bruno Rocha Martins[a,*], Michael Douglas Roque Lima[a], Udson de Oliveira Barros Junior[a], Larissa Sousa Villas-Boas Amorim[b], Francisco de Assis Oliveira[a], Gustavo Schwartz[c]

[a] Federal Rural University of Amazonia, Institute of Agrarian Sciences, Av. Presidente Tancredo Neves, 2501, 66077-830 Belém, PA, Brazil
[b] Management and Operational Center of the Amazonia Protection System, 66617-420 Belém, PA, Brazil
[c] Embrapa Eastern Amazon, P.O. Box 66095-100, Belém, PA, Brazil

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ABSTRACT

Mining contributes significantly to the world's economy. However, it brings strong environmental impacts, including the destruction of the original vegetation. In this way, the recovery of degraded areas by mining has been a mandatory procedure in many countries. With the objective to review this subject, a bibliometric analysis was carried out using scientific articles published in the period 1990–2018. A total of 700 articles in 171 journals were sampled. Ecological Engineering and Restoration Ecology were the journals with the largest number of articles. There was a significant increase of articles along time approaching the use of geotechnologies and arbuscular fungi. Recovered or recovering ecosystems were studied in 45 countries, mainly in Brazil, Australia, USA, China, and Spain. Coal and bauxite were the most common resources mined. The most frequent recovery methods were: seedling planting, direct seeding, natural regeneration, and hydroseeding, with techniques employed in some of them. In 35.71% of the articles, a small number of species (2–5) were used for the initial plant's establishment. The number of articles decreased as the number of both, plant species used in the initial recovery phase, and ecosystem's age increased. In monitoring, the most important indicators were classified as functional or functional plus structural. From the functional indicators, the Technosols or rebuilt soils were the most evaluated. Future perspectives on forests recovery includes methods tailored to peculiar features (soil and economic) of each ecosystem. For the forest recovery monitoring, the use of geotechnologies, mainly the Unmanned Aerial Vehicles (UAVs), as well as wildlife indicators tend to increase rapidly.

1. Introduction

Mining currently figures as one of most destructive economic activities over natural ecosystems. It brings various negative impacts to the environment, which starts with the complete removal of the local native vegetation and consequent wildlife disappearance (Parrotta and Knowles, 2001; Macdonald et al., 2015). Following this, the topographic disassembling is done when finally the ore mining starts, which usually results in strong hydro-biogeochemical changes in the ecosystem (Evans et al., 2015; Feng et al., 2019).

Due to the great economic and social importance of mining (Ranjan, 2019), it is inevitable that new mines cause the disruption of natural ecosystems. For this reason, the development and establishment of methods and techniques able to minimize initial negative effects and, after mining, to restore original ecosystems functions and services becomes a research priority. As the short- and long-term reestablishment of such functions and services is almost impossible, new ecosystems are created with new functions and services, different than those prior to mining. New ecosystems can evolve from the use of homogeneous planting of exotic arboreal species, agriculture, and livestock. In extreme cases of so deep and large mining pits, fresh water ecosystems can be created through artificial lakes (Lima et al., 2016).

To promote recuperation by restoration of a given terrestrial ecosystem, it is proven useful the employment of soil recovery methods. This can be developed by tree and/or bush planting using transplanting techniques, direct seeding, hydroseeding, and the promotion of natural

* Corresponding author.
E-mail addresses: walmerbruno@gmail.com (W. Bruno Rocha Martins), lima_florestal@outlook.com (M. Douglas Roque Lima), udson_engflorestal@outlook.com (U. de Oliveira Barros Junior), larissaamorim.engfl@gmail.com (L. Sousa Villas-Boas Amorim), francisco.oliveira@ufra.edu.br (F. de Assis Oliveira), gustavo.schwartz@embrapa.br (G. Schwartz).

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regeneration via topsoil storage and deposition. These are currently the most efficient ways to recover forests after mining. Recent research has focused on planting spacing (Bouchard et al., 2018), seeding with various species, green fertilization (Longo et al., 2011), use of topsoil from different mine sites (Jaunatre et al., 2014; Fowler et al., 2015; Bulot et al., 2017), and others, all aimed to find best combinations under lowest cost.

Regardless the method and technique used to rehabilitate degraded ecosystems, monitoring is required to understand the ecosystem trajectory (Martins et al., 2018). The data collected (variables or indicators), can be qualitative and/or quantitative, and they can also vary in time after the start of recovery process (Brancalion et al., 2015). Ecosystem indicators are classified in three main groups: (i) compositional or diversity, (ii) structural, and (iii) functional indicators (Dale and Beyeler, 2001; Ruiz-Jaén and Aide, 2005).

Compositional indicators are those related to living component of the ecosystem: present populations with plant or animal number of species, diversity indexes, life forms, and ecological groups (Noss, 1990; Taddeo and Dronova, 2018). Structural indicators come from the physical dimensions of the ecosystem's plants as the tree total height and diameter, biomass, litter layer, canopy cover, and crown diameter (Taddeo and Dronova, 2018). Functional indicators are related to the ecological or evolutionary processes of ecosystem, such as the return of wildlife and their ecological functions in ecosystems, the increase in soil fertility, nutrient cycling, and carbon sink (Noss, 1990; Dale and Beyeler, 2001; Taddeo and Dronova, 2018).

These variables can be assessed in several types of environments and provide the basis for legal regulations. Monitoring programs must be adapted to each environment, considering the ore's depth and biotic/abiotic features such as: climate, topography, soil, and vegetation typology. In this context, it is essential to understand, in a global perspective, how ecosystems recover following mining operations, as to define which indicators should be included in the monitoring planning.

For data compilation, bibliometrics comes as an efficient statistical method to qualify and quantify specific and pre-determined published scientific information about a given subject. Moreover, through bibliometric analysis it is possible to establish trends or perspectives and diagnose gaps that should be evaluated in new researches. Bibliometrics has been used previously to evaluate ecological restoration (Oliveira and Engel, 2011; Wortley et al., 2013; López-Barrera et al., 2017; Romanelli et al., 2018), and more specifically, ecological indicators for monitoring (Siddig et al., 2016; Gatica-Saavedra et al., 2017). Similar research to the present study was developed by Wortley et al. (2013) and Guan et al. (2019), who found an evolution in the number of works published with ecological restoration over time. Although such substantial advance, there are no bibliometric scientific works about recovery methods of degraded ecosystems by mining and their indicators for monitoring.

This work has the objective to tackle the following scientific questions: (i) what are the forest recovery methods that have been applied over degraded terrestrial ecosystems due to mining? (ii) What indicators were used to monitor the rehabilitation of these ecosystems? Our hypothesis is that, although there are a great number of methods available, seedling planting of native tree species is the most employed one, as mined areas usually have extremely low natural resilience, and seedling planting ensures greater initial control of plant insertion in the site. The main assessment indicators are classified as functional, especially those that are easy to collect and that reliably describe the ecosystem situation at a given time. To pursue this objective, a bibliometric analysis was performed including data of the last three decades (1990–2018) of studies in a global level on methods and indicators of forest restoration in mined ecosystems.

2. Methods

2.1. Data collection

A qualitative and quantitative literature review was carried out upon scientific articles published from January 1990 to December 2018, where scientific and/or technical biases observed in all searched authors and time periods could not be fully avoided. Only papers with Digital Object Identifier System (DOI) and published in English worldwide were included in this review. The searches aimed forest restoration methods after mining as well as their respective evaluation indicators. Articles on literature review and those developed in greenhouses were not considered in our research. Searches were done in English, using the following databases: “ScienceDirect (Elsevier) (https://www.sciencedirect.com)”, “JSTOR (https://www.jstor.org/)”, “SciELO (http://www.scielo.org/php/index.php), “Springer Link (https://link.springer.com/)”, and “Wiley Online Library (https://onlinelibrary.wiley.com/)”.

Keywords used for searches were: “restored”, “restoring”, “restoration”, “rehabilitation”, “reclaimed”, “reclamation”, “recovery”, “revegetation”, “reforested”, “reforestation”, “mining”, “mine”, and “mineral exploration”, always driven to forest ecosystems. These keywords could appear in the articles' title, abstract, or keywords (Fig. 1)

2.2. Analyzed variables

The variables analyzed were: countries where researches were carried out, type of ore mined, recovery methods of the degraded ecosystems, restoration techniques and/or techniques applied, initial number of plant species used to recover the environment, time of the ecosystem under recovery process, and the existence of monitoring indicators (Table 1). Indicators were classified in: compositional indicators as species diversity, life forms, and ecological groups; structural indicators, as plant height, diameter, and crown area and functional indicators as Technosols or tailings and rock waste chemical properties, nutrient cycling, and gases flow, according to the classification described by Ruiz-Jaén and Aide (2005).

2.3. Data analysis

Articles assessed were grouped from January 1990 to December 2016 in 3-year intervals (1990–1992, 1993–1995, 1996–1998, 1999–2001, 2002–2004, 2005–2007, 2008–2010, 2011–2013, and 2014–2016) and in a 2-year interval, from January 2017 to December 2018. Journals with the largest number of articles on this subject were recorded and a mapped, indicating the study areas in a global level.

Descriptive statistics and regression analysis were performed and presented in histograms and Venn diagrams. For these analyses, tools of Microsoft® Office Excel version 2016 and the statistical software R version 3.4.3 (R Development Core Team, 2016) were used.

3. Results and discussion

3.1. Evolution of the number of scientific articles published

During 28 years there was an exponential increase of articles published on the subject “recovery of degraded forest ecosystems by mining”, as shows the regression analysis in Fig. 2.

The increase in number of articles on restoration of degraded areas is due to the global relevance reached of the topic, as a response to negative environmental changes caused by mining over different ecosystems (Oliveira and Engel, 2011). Mining companies and research institutions have collaborated more closely with the goals to develop more rapid and less expensive methods to recover and monitor ecosystems under restoration processes (Guan et al., 2019). Mining companies have adopted geotechnology tools and techniques to monitor

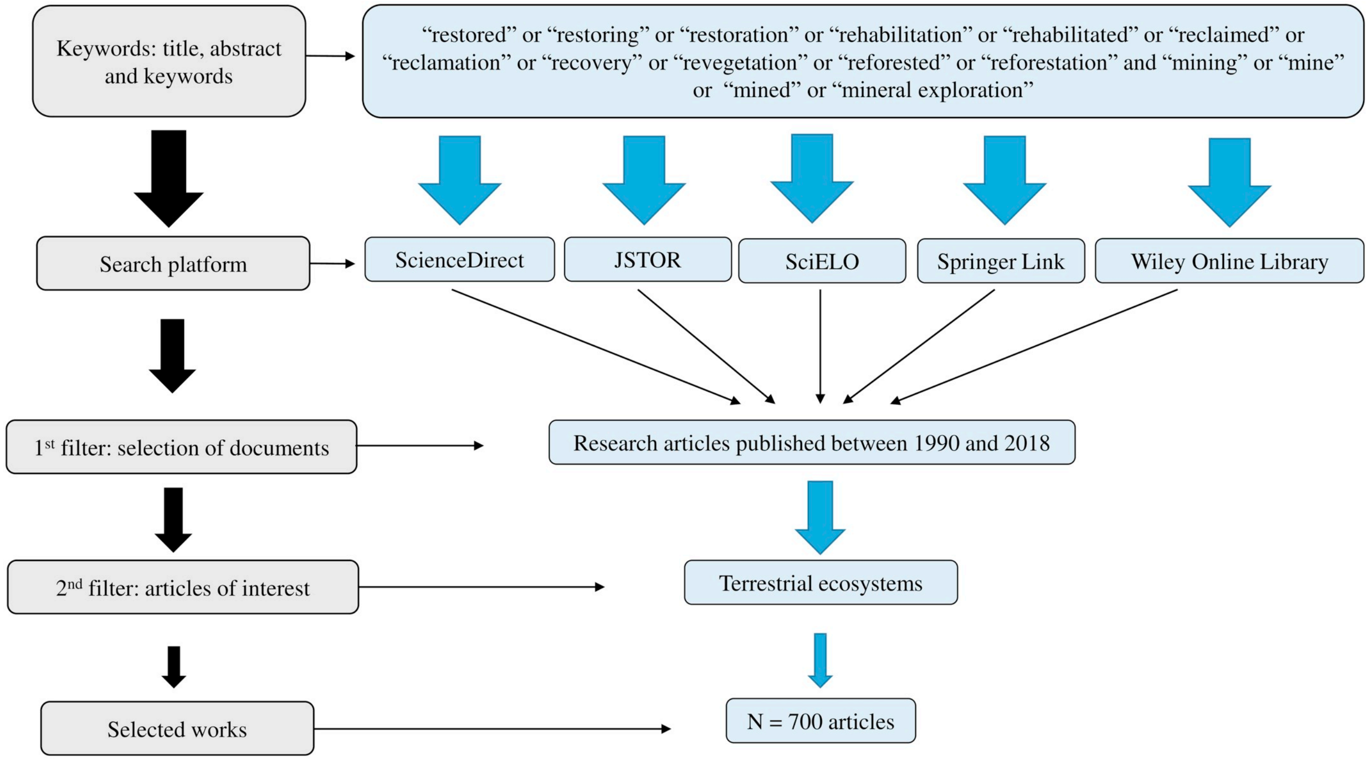

Fig. 1. Proceedings and criteria established to run the bibliometric analysis about recovery methods and ecological indicators used in mining activities in a global level. N = total number

large areas of mined environments, with lower operational costs and facilitated inspection by environmental agencies (Erener, 2011; Yang et al., 2018; Karan et al., 2016; Moudrý et al., 2019). Among the use of new biotechnologies and phytotechnologies, there has been a significant increase in articles on arbuscular fungi, which provide higher plant survival, establishment, and growth (Li et al., 2015; Shuab et al., 2018; Kumar et al., 2018; Prado et al., 2019). Collaboration between mining companies and research institutions also helps the companies to better comply with legal environmental requirements imposed by each country, and to publicize research outcomes through scientific papers.

According to the search criteria, a total of 700 articles in 171 journals were sampled. Twenty journals summed up 58.6% of the total number of articles, where the most representative journals were Ecological Engineering (10.6%) and Restoration Ecology (5.9%), considering the total number of publications in the period 1990–2018 (Fig. 3). These journals appear also among the most relevant (regarding the number of articles) in the works of Wortley et al. (2013), about indicators of ecological restoration, and Guan et al. (2019), using bibliometric methods to assess restoration.

Papers on recovery of degraded areas increased over the last nine years, when compared the number of articles in three separated decades (Fig. 3). This happened because of the advent of new journals and the subject inclusion in the scope of more traditional journals. Besides the subject importance, there is an increment on the journals' issues published every year. The journal Restoration Ecology had four issues per

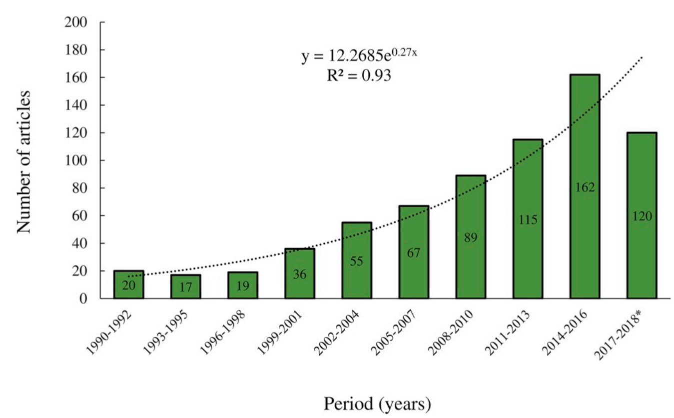

Fig. 2. Exponential growth of the number of articles published on the subject "recovery of degraded forest ecosystems by mining" worldwide over the last three decades (1990–2018) in 3-year periods. *Two-year period.

Table 1
Qualitative and quantitative variables and their criteria and indicators of evaluation approached in the sampled articles about the recovery methods of degraded ecosystems by mining activities in a global level during the period 1990–2018.

Variable	Criteria and indicators of evaluation
Mining place	Country where the resource was mined.
Resources mined	Resource removed from the environment: metallic and/or non-metallic.
Recovery methods	Method(s) used to recover vegetation of degraded ecosystems. Example: seedling planting, seeding, hydroseeding, and natural regeneration.
Techniques applied	Variations of the method applied. Example: fertilized planting, non-fertilizing planting.
Number of plant species used	Number of plant species used in the recovery initial phase.
Recovery time (years)	Time elapsed since the recovery beginning until the end of the research work.
Evaluation indicators	Qualitative and quantitative indicators evaluated along monitoring: compositional, structural, and functional indicators.

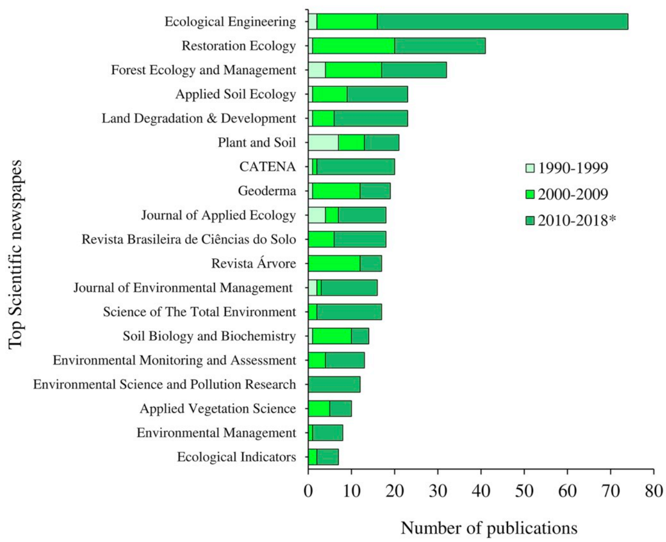

Fig. 3. Number of articles about the subject "recovery of degraded forest ecosystems by mining" distributed among the 20 most representative scientific journals in the period 1990–2018. *Two-year period.

year in 1993, and now it publishes six issues per year, while the journal Ecological Engineering increased from four issues in 2006 to 12 issues, currently.

3.2. Distribution of the study areas in the articles published

Articles ($n = 700$) were distributed in 44 countries, where Brazil ($n = 100$), Australia ($n = 96$), USA ($n = 87$), China ($n = 78$), and Spain ($n = 46$) were those with the highest number of researches on degraded environments due to mining, with 58.1% of the total articles sampled (Fig. 4).

When countries are divided per continent, Europe presented most of the countries (16) in number of papers about recovery of degraded areas by mining, followed by Asia (9), South America (6), Africa and North America (five each), and Oceania (3) (Fig. 4). These results show that mining is a common economic activity in all continents, and there is worldwide rising concern that degraded areas by mining must be recovered (Monteiro et al., 2019; Tuokuu et al., 2019) (Fig. 5). Moreover, they show the importance of research involving the recovery of degraded ecosystems by mining in a global scale (Fig. 5).

Besides scientific and technological advances, those countries with large number of articles on this subject are also advanced in legal and economic aspects of ecosystems rehabilitation. This occurred, among other causes, due to hundreds of abandoned mines, mainly of metallic ores, throughout the world, which caused serious environmental impacts. As a consequence of this, mines were closed because of the very negative public opinion on mining activities and their impacts on the environment (Venkateswarlu et al., 2016).

3.3. Mineral diversity

Regarding the mined natural resources, 35 types of resources were found, being 24 metallic and 11 non-metallic minerals. Most of the studies, 66.6%, were on non-metallic ores, where 69.3% of them involved coal mining (Fig. 6A). Coal has a significant importance, since it contributes to approximately one third of all energy produced in the world (7585 Mt. produced in 2017), with perspectives on production to remain until 2023 (IEA, 2018). Such situation brings concerns to researchers, because coal is a non-renewable resource with strong environmental impacts (carbon release to atmosphere and heavy metal emissions) as well as social, and even economic impacts (Jin and Bian, 2013; Surber and Simonton, 2017).

USA and China together presented the largest number of articles about forest recovery after coal mining, with 36.8% of the studies. The two countries are therefore not only the world biggest coal producers (IEA, 2018), but also the countries with most of the research on methods to recover degraded areas after coal mining. The USA and China have the top world's institutions in terms articles published on the topic (Guan et al., 2019).

In relation to metallic ores, bauxite (used to obtain Aluminum) was the most frequent in published articles (Fig. 6B), being China, Australia, and Brazil the biggest world producers (Associação Brasileira do Alumínio, 2017). Large deposits of lateritic bauxite occur near the Equator line, where high temperatures and relative humidity favor chemical leaching and consequent formation of this ore (Meyer, 2004). The largest bauxite deposits are found in plateaus of the Amazon basin, in Brazil, Venezuela, Guyana, and French Guiana (Monsels and Van Bergen, 2019). New areas of bauxite mining are expected to be consolidated in this region. This will demand further studies on methods and techniques to reduce time and cost of forest recovery, with the permanent objective to maintain native biodiversity and local populations under no mining negative impacts.

3.4. Recovery methods for degraded areas by mining

Six recovery methods to recover degraded areas by mining were found: seedling planting, direct seeding, hydroseeding, natural regeneration, seedling transplanting, and artificial perch (Fig. 7). The two last methods had only one study each, so that they were not included in the Venn diagram. In 84 (12.0%) articles, reforestation methods applied were not clearly described throughout the text.

Seedling planting is widely the most used recovery method, being present in 54.1% of the papers. This method presents the advantage of using species from different successional groups and the best adapted species to the local soil and climate conditions (Stanturf et al., 2014; Villacís et al., 2016).

Other methods, however, showed the tendency to become more frequent, such as direct seeding and natural regeneration. In direct seeding it is necessary a detailed planning, since the acquirement of high quality seeds depend on a precise time for seed collection in matrix trees. Moreover, there is a strong demand on quality seeds and public policies to encourage tree seeds and seedling production of native species (Moreira da Silva et al., 2017; Schmidt et al., 2019; Elzenga et al., 2019). On the other hand, many reports have shown that seeding of crops or grasses can protect and improve the initial soil conditions for further inclusion of trees (Melloni et al., 2003; Silva et al., 2016; Józefowska et al., 2017; Rawlik et al., 2018).

Natural regeneration can be classified as spontaneous or assisted. Spontaneous natural regeneration occurs when the area is abandoned or, otherwise, left undisturbed after mining. This method requires many decades for vegetation establishment, since there are no human interferences to speed up the process (Holl and Aide, 2011). Assisted natural regeneration depends on human interventions, as the transference of topsoil, rich in seeds and other propagules, for soil re-coverage (Koch and Samsa, 2007; Macdonald et al., 2015; Ferreira and Vieira, 2017; Dhar et al., 2019).

3.5. Techniques used in forest recovery methods

In each recovery method, some experimental techniques or treatments were employed (Table 2) as, for example, different tree species for reforestation (Cleveland and Kjelgren, 1994; Melloni et al., 2003; Burney and Jacobs, 2018), green fertilization (Longo et al., 2011; Sbaffoni et al., 2015), different planting spacing (Villa et al., 2016; Bouchard et al., 2018), different substrates (Martínez-Ruiz and Marrs, 2007; Asensio et al., 2013; Yada et al., 2015) and seeding of various plant life forms in two depths (Spargo and Doley, 2016).

Those techniques have been tested worldwide (Stanturf et al.,

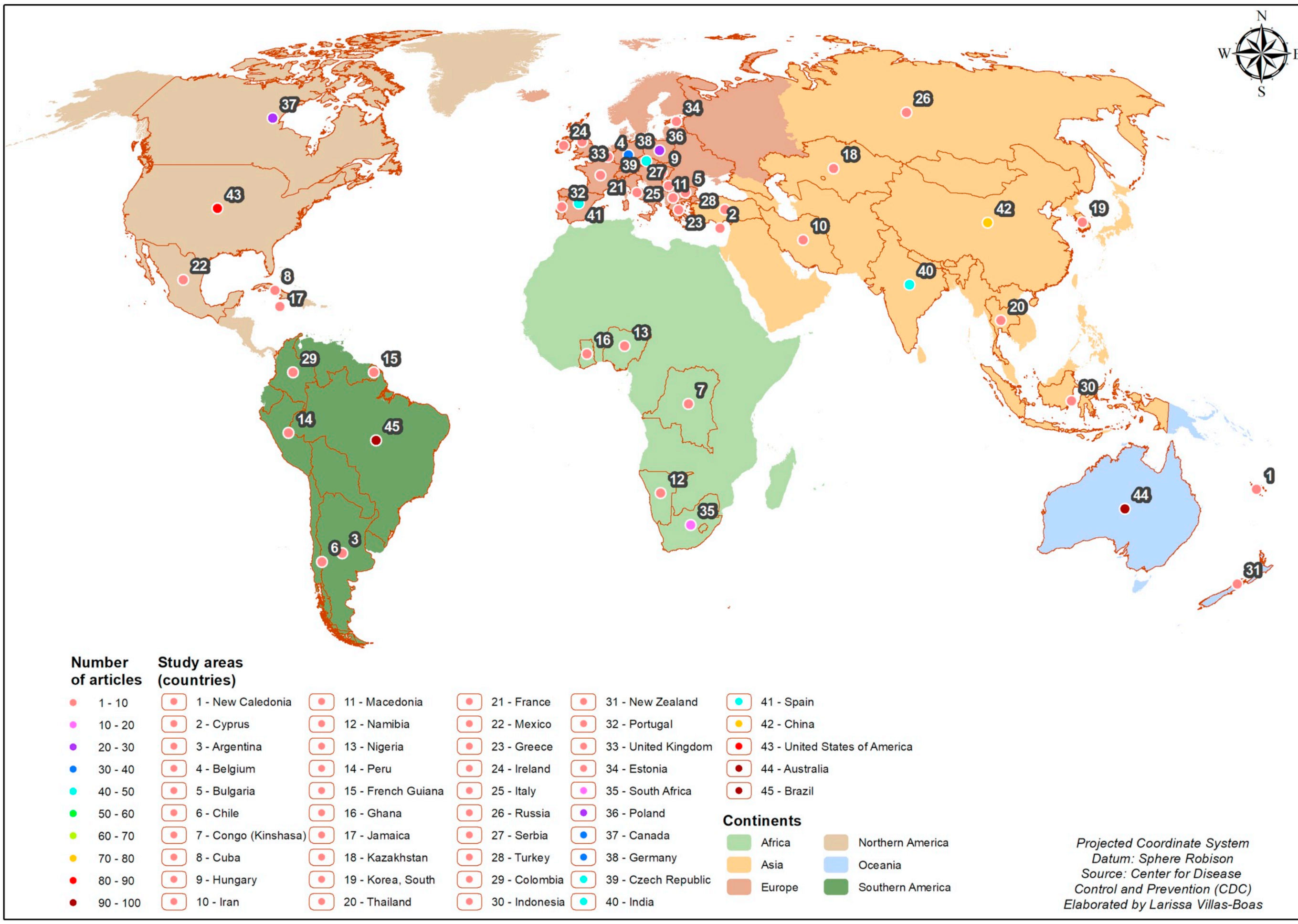

Fig. 4. Global distribution of the articles published in the period 1990–2018 about degraded areas due to mining activities.

2014), with the objective to overtake the main issues of degraded areas by mining, as the choice of non-adapted plant species, soil compaction, erosion, plant nutritional deficiency, and slow return of native animal species.

From the 700 sampled papers, 61.1% reported the usage of only one technique for a given recovery method for degraded ecosystems due to mining. Thus, it is reasonable to infer two possible causes for such result: there are standard recovery protocols for each mining company or, these companies face financial resources limitations for research on recovery methods improvement. Despite of this, in seedling planting of tree or shrub species and in seeding there was a higher number of techniques that, in 1.4% of the cases, > 10 techniques were adopted (Table 2).

3.6. Number of species for recovery and ecosystems age

Studies with no species were originated from the spontaneous or assisted natural regeneration, where no new plant species was introduced (Fig. 8). In 25.9% of the articles, the number of species initially included was not presented. In these cases, more emphasis was given to soil monitoring or other ecological indicators rather than plant species.

The number of articles decreased as the number of plant species used in the initial recovery phase increased. The most frequent number of initial species varied from two to five in the majority of the studied ecosystems (Fig. 8). Whether the use of a single species for ecosystem restoration is doubtful on the future services functioning, it does not mean that a large number of species will guarantee these services. In this case, the succession processes would normally start with a low number of well-adapted species and the species richness would increase along time (Chazdon, 2014; Stanturf et al., 2014). In the seedling planting method, the average number of species used in the initial phase of recovery tended to be reduced over the last three decades. In average, 15.43 ± 21.79 species were used in the period 1990–1999, 8.67 ± 22.36 in 2000–2009, and 7.84 ± 21.86 in the period 2010–2018. Regarding the average number of species per country and the type of ore mined, the data did not permit predictions on trajectories, since in many articles, the number of species used in restoration programs are not precisely reported, even the planted species.

Concerning the ecosystem age, the number of articles decreased as the study ecosystem age increased. Most of the studies were carried out during the first 10 years (Fig. 9). Studies on ecosystems over than 100-year-old were also found, probably to be used for comparisons with more recent sites, working as a control of the possible trajectory to be followed by an effective recovery project.

Articles with older study ecosystems involve primarily research on recovery indicators as birds (Bulluck and Buehler, 2006; Kirby et al., 2009; Šálek, 2012), lepidoptera (Tropek et al., 2013; Cusser and Goodell, 2013), arthropods (Heneberg and Řezáč, 2014R Development Core Team, 2016; Tizado and Núñez-Pérez, 2016), and mammals (Nichols and Grant, 2007; Owusu et al., 2018). In these studies, vegetation is not monitored since it is at least partially established, not demanding further interventions. However, the return of native animal

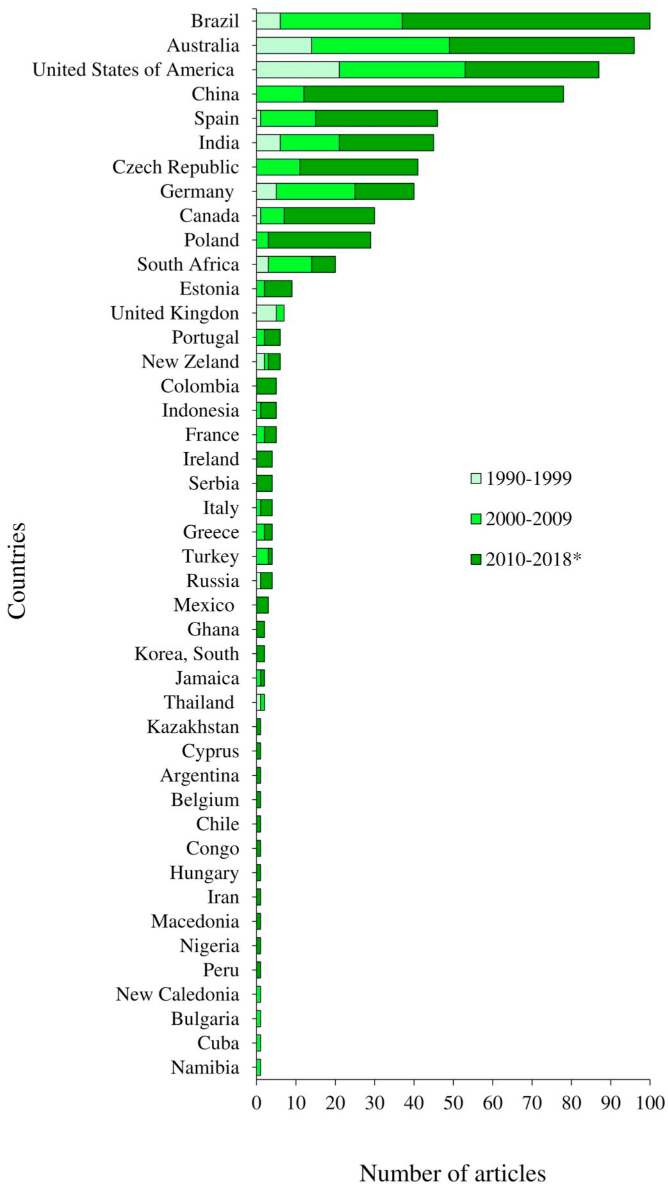

Fig. 5. Number of articles about the subject "recovery of degraded forest ecosystems by mining" published by country in the last three decades (1990–2018) over three-year periods. *Two-year period.

species becomes the main objective of such studies, especially when rare species are involved, since they can have essential functions on seeds dispersal, pollination, and energy flux throughout ecological webs (Cristescu et al., 2012; Baur, 2014).

3.7. Classification of the recovery indicators

A total of 72.2% of the assessed indicators were classified as functional indicator (Fig. 10). The preference for evaluating this type of indicator shows a concern not only with the ecosystems composition and structure, but mainly with their functioning and services conservation. This concern embraces the assumption that is more difficult to reintegrate functions than to reintegrate the ecosystem structure and composition (Hanberry et al., 2015; Ribeiro et al., 2018).

Even though the number of functional indicators is much higher, the compositional and structural indicators are not less important, because they are fully interlinked to the functional indicators. This occurs because of flora and fauna diversity, considering composition indicators, will promote a better balanced ecosystem with a constant energy flux through the forest and wildlife (Aerts and Honnay, 2011). This balance will depend on the time elapsed since the introduction of plant species in the ecosystems, so these species can work as catalysts of the natural regeneration, establishing vertical structures or strata (Stanturf et al., 2014).

From the functional indicators, 54.4% are directly related to chemical, physical, and biological soil attributes (Fig. 11), which corroborates the results of Gatica-Saavedra et al. (2017). Despite of this, their contribution is even larger when these attributes are described in papers as complementary information (81.2%), so they support results of other indicators used to characterize the ecosystem.

During the mining process, the original soil is completely destroyed. Hence, the total or partial soil recovery becomes a challenge to provide plants attaining the minimal conditions to thrive (Feng et al., 2019). Post-mining rebuilt soils are defined as Technosols or minesoils, since they are created from rock and debris (IUSS Working Group, 2006; Ahirwal and Maiti, 2018; Feng et al., 2019).

Few articles approach the biological properties of Technosols, where the soil macro-, meso-, and microfauna are described (Fig. 11). The soil fauna is responsible, among other functions, to decompose the organic matter, transforming it in to humus to be absorbed by plants. The speed of this process varies according to several abiotic factors such as temperature, relative humidity, and the space heterogeneity (Filser et al., 2016). The properties of rebuilt soils must be determined to achieve an efficient indicator in describing, for example, plant establishment and growth. Domínguez-Haydar et al. (2019), suggest an interesting General Indicator of the rebuilt Soils Quality (GISQ), based on the combination of chemical, physical, and biological soil properties.

Topsoil has been used to help in the propagation of seedlings and on the establishment of plants in Technosols, which is a promising alternative (Aradottir and Hagen, 2013). However, key practices can improve and/or preserve the chemical and mostly microbiological features of this material, such as storage methods, storage time, and thickness of the topsoil layer removed from the ecosystem (Macdonald et al., 2015).

3.8. Perspectives and challenges of restoration methods and indicators evaluation

Seedling planting has been the most common recovery method used in research focused on degraded mine sites over the last 28 years, likely because of its high certainty level in having plants in the ecosystem and on the tolerance to adverse conditions found after mining. The use of seedlings was applied not only in the total area, but also in vegetation cores or islands, combined with trees harvested through vegetation suppression in operation in other sectors of mines. Seedling planting after spreading topsoil can also be done, which has been strongly supported by mining companies due to its low cost and on limitations to get seeds for seeding.

Regardless of being the most common, seedling planting is not a universal recovery method of mined areas, since the method choice depends on several factors as (i) size of the area to be recovered and its distance from a remaining vegetation; (ii) availability of natural and financial resources; (iii) operational capability of topographic reconformation and the use of topsoil; and (iv) availability of skilled labor. Hence, the use of numerous recovery methods could be recommended. This could become more common in a near future, where "precision recovery" methods would be deployed in degraded areas divided in smaller plots, providing the best treatment for each plot.

Unmanned Aerial Vehicles (UAVs) are a tool in which usage has

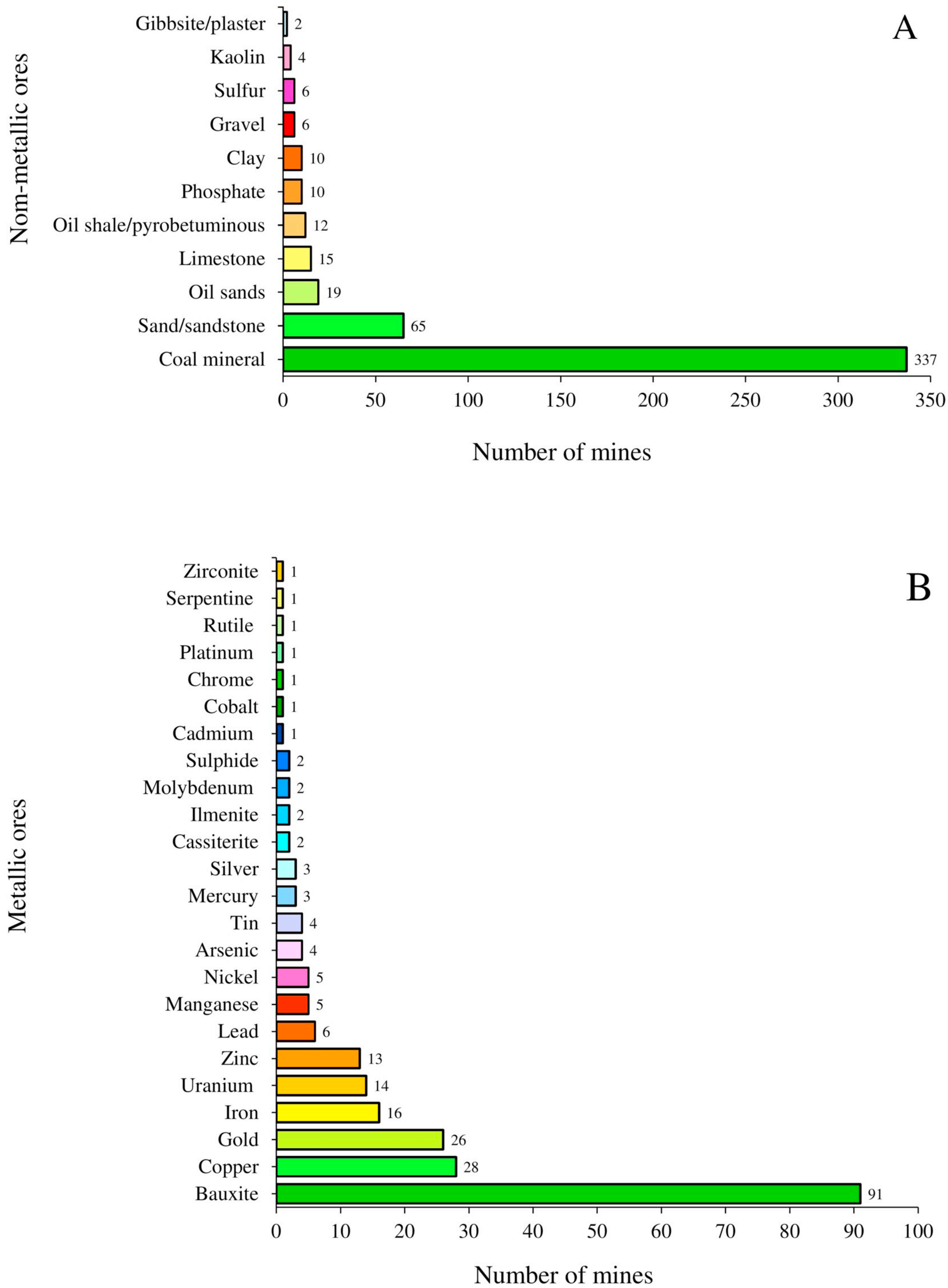

Fig. 6. Number of mines by type of ore found in scientific articles surveyed about the subject "recovery of degraded forest ecosystems by mining" in the last three decades (1990–2018): non-metallic (A) and metallic (B) ores.

been increasing for aerial monitoring of vegetation through remote sensing. Although in the 700 sampled scientific article, there was only one on the employment of UAVs to monitor mining areas (Whiteside and Bartolo, 2018), many studies use geotechnologies. Such studies used Normalized Differences Vegetation Index (NDVI), with free images (usually Landsat), and assessments over time (multitemporal analysis), which have a relatively large coverage area and little detail of the minor features (Fernández-Manso et al., 2012; Erener, 2011; Karan et al., 2016). However, recently, high spatial precision sensors have been coupled to the UAVs to obtain multi spectral images, where it is possible to see ecosystems details of the recovering areas (Moudrý et al., 2019; Padró et al., 2019; Ren et al., 2019). Once acquisition costs of some sensors, such as LiDAR (Light Detection and Ranging), have decreased, the number of suppliers will probably increase. So, the purchase of such equipment and its sensors by companies and environmental inspection agencies tends to improve work safety and decrease

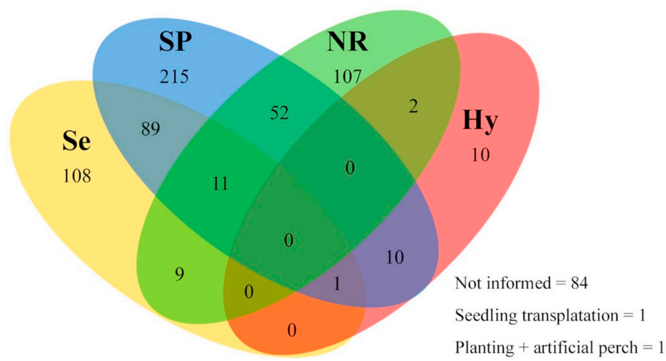

Fig. 7. Venn diagram with the main recovery methods found in scientific articles surveyed about the subject "recovery of degraded forest ecosystems by mining" in the period 1990–2018: SP (Seedling planting); NR (Natural regeneration); Se (Seeding); Hy (Hydroseeding).

ergonomic issues, reducing costs and time to work on large mining areas (Ren et al., 2019).

Studies of native animal species, including soil macro-, meso-, and microfauna, increased by 73% from 2001 to 2010 over the previous decade and 26.1% from 2011 to 2018 over 2001–2010. These results highlight the increasing interest of researchers for some groups of native animal species, mainly those more sensible to mining impacts as endemic and/or endangered species due to the habitat losses (Dias et al., 2019).

4. Final remarks

By the application of bibliometric analysis, it was shown that the number of articles about recovery of degraded areas by mining has been increasing exponentially over the last 28 years. These studies were recorded in ecosystems distributed in all of the world, but mainly in Brazil, Australia, USA, China, and Spain, where the main mined resources are coal and bauxite.

The main recovery methods of degraded areas by mining were seedling planting, direct seeding, natural regeneration, and hydroseeding. These recovery methods presented variation in techniques or treatments usually aimed to promote higher efficiency and lower cost. During the initial phase of ecosystem rehabilitation, most of the articles presented a number of initial plant species between two and five and most of the recovering ecosystem were lower than 10-year-old. The number of planted species has decreased over the past three decades without a clear tendency in time by country or type of ore mined.

Functional indicators were the most common during the recovery monitoring, which strongly contributed for the soil variables of the Technosols, specially the chemical attributes. Based on the analysis of 700 articles, future perspectives include the recovery methods according to the specific features of each site and to the financial conditions of mining companies. We recommend that future research on Technosols building takes into account the correct use of topsoil and organic fertilizers that can be managed through large machines. Thus, the use of topsoil and organic fertilizers can be more efficient and environmentally friendly practices adopted by mining companies. We also suggest scientific work on enrichment recovering of ecosystems and the inclusion of various plant species over the ecological successional time according to their ecological characteristics. This will improve the development of soil fauna and the return of native animal species, since they are essential elements for ecological restoration.

In relation to ecosystems monitoring, the use of geotechnologies will continue to increase, especially the UAVs for assessing vegetation cover. Furthermore, research on wildlife also tends to increase, following the tendency observed over the last 28 years.

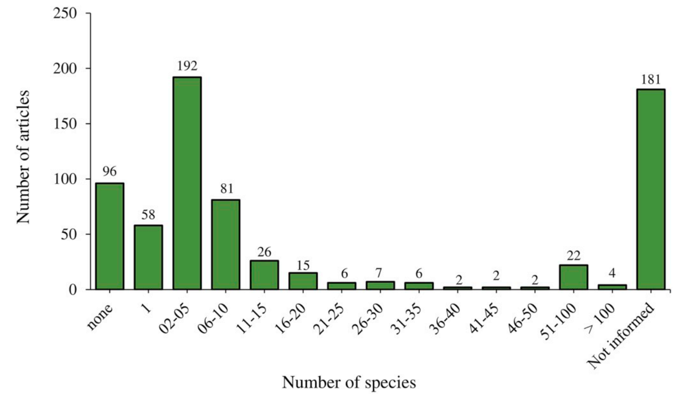

Fig. 8. Number of articles in relation to the number of plant species initially used to recover degraded ecosystems by mining during the period of 1990–2018 at global level.

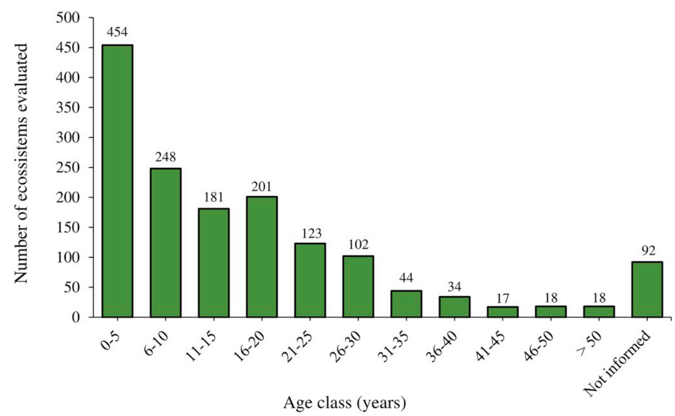

Fig. 9. Number of ecosystems per age class of recovered or in process of recovering, in the articles sampled during the period 1990–2018 at global level.

Table 2
Number of articles with different techniques or treatments according to the recovery methods applied in degraded ecosystems by mining over the last three decades (1990–2018).

Number of techniques/treatments	Number of articles by method									
	SP	NR	Se	Hy	PS + RN	PS + Se	PS + Hy	NR + Se	NR + Hy	PS + NR + Se	PS + Se + Hi
1	143	101	70	9	30	58	5	6	1	4	1
2–3	39	3	17	0	9	12	2	3	1	3	0
4–5	18	1	13	1	4	8	3	0	0	3	0
6–7	9	1	4	0	8	4	0	0	0	0	0
8–9	2	1	1	0	1	5	0	0	0	0	0
≥10	4	0	3	0	0	2	0	0	0	1	0

SP: Seedling planting; NR: Natural Regeneration; Se: Seeding; Hy: Hydroseeding.

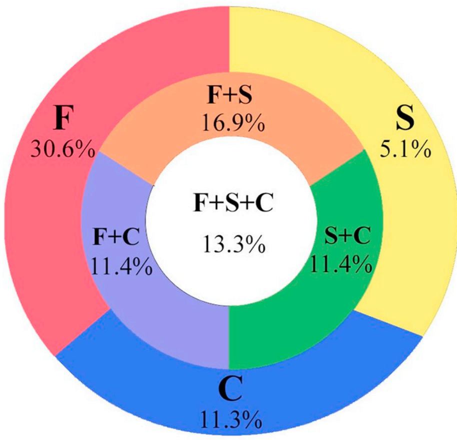

Fig. 10. Indicators classification in structure, function, and composition during monitoring of ecosystems in recovering process due to mining activities in articles published during the period 1990–2018. C = Compositional indicators, S = Structural indicators, and F = Functional indicators.

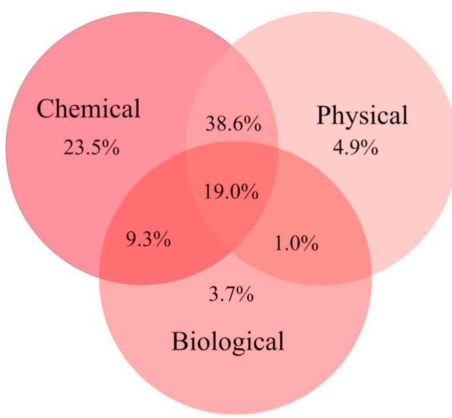

Fig. 11. Functional indicators related to chemical, physical, and biological attributes of Technosols or rebuilt soils during ecosystem monitoring of post-mining recovery process in articles published during the period 1990–2018 in a global level.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2019.105707.

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