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REVIEW

Mine land rehabilitation in Brazil: Goals and techniques in the context of legal requirements

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Abstract Environmental legislation in many countries demands the rehabilitation of degraded areas to minimize environmental impacts. Brazilian laws require the restitution of self-sustaining ecosystems to historical conditions but ignore the emergence of novel ecosystems due to large-scale changes, such as species invasions, extinctions, and land-use or climate changes, although these novel ecosystems might fulfill ecosystem services in similar ways as historic ecosystems. Thorough discussions of rehabilitation goals, target ecosystems, applied methods, and approaches to achieving mine land rehabilitation, as well as dialogues about the advantages and risks of chemical inputs or non-native, non-invasive species that include all political, economic, social, and academic stakeholders are necessary to achieve biological feasibility, sociocultural acceptance, economic viability, and institutional tractability during environmental rehabilitation. Scientific knowledge of natural and rehabilitating ecosystems is indispensable for advancing these discussions and achieving more sustainable mining. Both mining companies and public institutions are responsible for obtaining this knowledge.

Keywords Biological invasions · Environmental legislation · Historical reference systems · Novel ecosystems · Sustainable mining

INTRODUCTION

Mining activities generating socioeconomic welfare (Matlaba et al. 2017) are responsible for abrupt land-use changes worldwide (Souza Filho et al. 2016). Although the spatial extent of land degradation by mining is lower than that of other land-use changes, such as agriculture and cattle ranging (Franks 2015), its intensity is greater because of the complete suppression of vegetation, removal of topsoil layers, and eventual contamination of soils by toxic residuals (Bisone et al. 2016). Mining is restricted to areas containing mineral deposits and often increases pressure on rare, endemic or even endangered ecosystems with reduced spatial extents, such as serpentine or metalliferous ecosystems, e.g., the ferriferous savannas or *cangas* in Carajás Mineral Province, Eastern Amazon, Brazil (Skirycz et al. 2014). Environmental laws require compensation measures for impacts on biodiversity and natural resources in many countries (Richardson 2016), including Brazil. For example, mining companies are obliged to mitigate negative effects on biodiversity and ecosystem services by rehabilitating or restoring degraded areas (Aronson et al. 2011). Despite three decades of intense research on restoration ecology (Jordan and Lubick 2012), a plurality of sometimes contradicting definitions of terms, such as rehabilitation and restoration, the lack of legal specifications regarding restoration goals (Higgs et al. 2014) and uncertainties regarding management strategies aggravate successful environmental restoration (Perring et al. 2016), especially in megadiverse, tropical ecosystems (Virah-Sawmy et al. 2014), such as those in Brazil, which also contains some of the world's largest mineral reserves (e.g., Skirycz et al. 2014).

The Society of Ecological Restoration defines restoration as the complete restitution of ecosystem structure and functioning to its historic trajectory after degradation beyond its natural resilience threshold (Fig. 1, SER 2004). Rehabilitation, in contrast, refers to any enhancement in regard to ecosystem functioning and structure, independent of whether full restoration is achieved or not. By definition, restored ecosystems thus differ from further outcomes of rehabilitation activities, i.e., any enhancement of a

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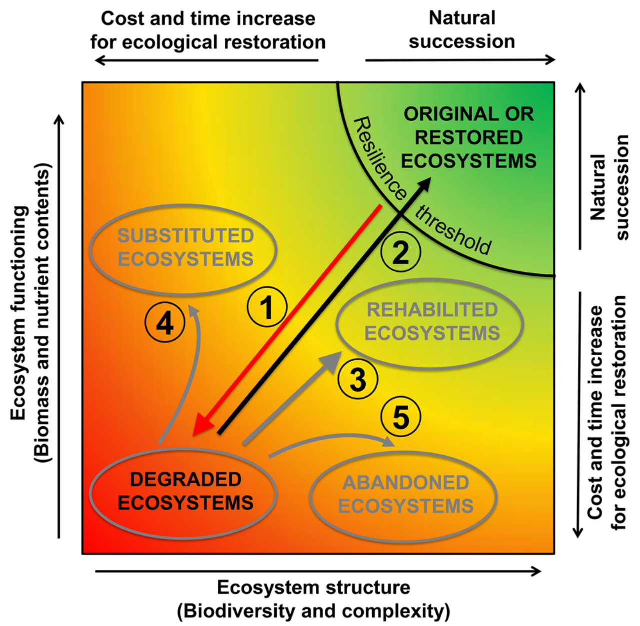

Fig. 1 The concept of degradation (1), ecological restoration (2) and alternative pathways, such as rehabilitation (3), substitution (4), and abandonment (5) in terms of ecosystem functioning and structure as defined by the Society of Ecological Restoration (SER 2004). In addition to possessing higher performance of ecosystem functions and more complex and diverse structures, restored ecosystems differ from all other possible outcomes after degradation in their natural resilience, i.e., the ability to recover from disturbances without external inputs. Substituted ecosystems include all kinds of managed agro-ecosystems; abandoned ecosystems are, for example, areas invaded by exotic species without human interference. The term rehabilitation refers to any enhancement with respect to ecosystem functioning and structure, independent of whether full restoration is achieved

degraded site, because ecological succession solely regulates important ecosystem processes, such as community dynamics, nutrient cycling, or energy flow, once ecosystem resilience is restored (e.g., Thompson et al. 2012; Derhe et al. 2016). Despite this clear statement, the definition of rehabilitation or restoration goals in practice is not straightforward, as global changes affect the composition, structure, and functioning of entire ecosystems (Feeley and Selma 2016). Climate changes shift the distribution ranges or cause the extinction of species, communities, and entire ecosystems (Bulleri et al. 2016). Furthermore, biological invasions following the introduction of non-native species alter ecosystem functioning (Simberloff 2015), and land-use changes, such as habitat loss and fragmentation, affect ecosystem structure by the removal of apex predators (Newsome et al. 2017) or edge effects (Matos et al. 2017).

Considering rehabilitation and restoration measures featuring temporal scales from decades to centuries (i.e., Liebsch et al. 2008), Richardson and Lefroy (2016) suggested the need for governance stimulating multifactor, collaborative processes, and multigenerational efforts to achieve biological feasibility, sociocultural acceptance, financial viability, and institutional tractability for rehabilitation and restoration projects. In contrast, extant environmental legislation focuses on the remediation of contaminated soils and recovery of endangered species, and it defines only biodiversity offsets, obliges mitigation strategies, and regulates sanctions according to polluter pays principles; possible improvements to the environment by rehabilitation or restoration receive little or no attention (Palmer and Ruhl 2015).[1]

In Brazil, one of the world's most important mining countries, a wide variety of laws, presidential decrees, and instructive norms regulate mine land rehabilitation and restoration (e.g., Aronson et al. 2011). The aim of this review article is to discuss the compatibility of these legal norms with modern concepts in restoration ecology in order to outline routes for the successful planning and realization of environmental rehabilitation and restoration projects after mining. The following chapters (i) review Brazilian legal norms regulating the rehabilitation of degraded areas, (ii) revise actual restoration techniques, and (iii) discuss modern goals in restoration ecology before recommendations regarding more effective planning and execution of environmental rehabilitation are given. This study is based on a comprehensive literature review of each of these areas. The relevant legislation was identified based on legal expertise and main publications in these areas (Aronson et al. 2011).

THE LEGAL SETTING IN BRAZIL

Since 1988, the Brazilian constitution has declared the right of all citizens to benefit from an ecologically equilibrated environment and has highlighted the obligation of governmental agencies to defend, preserve, and restore ecological processes and the diversity of genes, species, and ecosystems for present and future generations. It orders

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[1] The Australian Environmental Protection and Biodiversity Conservation Act from 1999, for example, lacks references to the entire restoration process, and the Australian Environmental Restoration and Rehabilitation Trust Act of 1990 lacks definitions of important terms, such as restoration and rehabilitation. The Canadian Environmental Protection Act of 1999 applies inconsistent language using undefined terms, such as 'remediate,' 'rehabilitate,' and 'repair' (Richardson 2016). In the USA, the Surface Mining Control & Reclamation Act (SMCRA) of 1977 obliges mining companies to establish diverse, self-regulating vegetative cover similar to pre-mining communities unless the application of non-native species is necessary to achieve the intended post-mining land use. In India, the Mineral Conservation and Development Rules of 1988 demand that mining companies revegetate degraded areas immediately, requiring the reutilization of topsoil, but specifications of which floral elements should be used are lacking.

the rehabilitation of degraded areas by the originator and constitutes penalties in the case of infringement.

To preserve, enhance, and rehabilitate environmental quality, the Brazilian National Environmental Act (Law 6938 from August 31st, 1981) authorizes the National Environmental Council (CONAMA from *Conselho Nacional de Meio Ambiente*) as the advisory and deliberative body for national environmental policies among Brazilian institutions. The council develops licensing standards for impacts and decides on fines and penalties.[2] The executive bodies forecasted in the National Environmental Act are the Brazilian Institute for Environment and Natural Renewable Resources (IBAMA from *Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis*) and the Chico Mendes Institute for Conservation of Biodiversity (ICMBio from *Instituto Chico Mendes de Conservação de Biodiversidade*), which is responsible for (mining) activities within conservation units. Both institutions develop activities to preserve and conserve natural patrimony, control the use and exploitation of natural resources, and grant environmental licenses for mining and other enterprises.

Environmental licensing requires environmental and socioeconomic risk assessments that describe in detail the significant impacts caused by the planned enterprise, including effects on biodiversity, loss of natural resources, and social or socioeconomic effects (Decree 99 274/90, Law 6938/81, CONAMA Resolution 237/1997). Based on these assessments, the magnitude of environmental compensation is outlined (Lei 9985/2000, Decree 4340/2002, CONAMA Resolution 371/2002). The Plan for Rehabilitation of Degraded Areas (PRAD from *Projeto de Recuperação de Áreas Degradadas*) is a document describing in detail all planned and realized rehabilitation activities. Planned rehabilitation activities and further environmental liabilities, i.e., environmental commitments to avoid, indemnify, or compensate risks or further impacts, are presented to the licensing agencies (Fig. 2); their non-compliance results in withdrawal of the operator license.

CONAMA, IBAMA and ICMBio released resolutions or normative instructions to regulate rehabilitation activities on degraded landscapes. Furthermore, the proper National Environmental Act and Presidential Decree no 5746 (from April 5th, 2006) and the Native Vegetation Protection Law (NVPL from *Lei de Proteção da Vegetação Nativa*, Law 12 727 from October 17th, 2012), also known as the Brazilian Forest Code, define rehabilitation and restoration activities. As shown in Table 1, different legal norms differ not only in their objective but also in their restoration goals. Only two of seven norms require the restoration of ecosystem functions or processes as postulated by classic approaches in restoration ecology (e.g., SER 2004; Higgs et al. 2014), a further two require the rehabilitation of native ecosystems and/or physiognomies, whereas the Normative Instruction from ICMBio aims to substitute exotic invasive species cover with native species.

By Brazilian legal norms, the term ‘restoration’ is defined as restitution of ecosystems as close as possible to the natural conditions. This definition is compatible with the postulations from SER (2004), whereas the definition of rehabilitation differs between SER (2004) and the Brazilian legislation. In the latter, rehabilitation represents the restitution to a non-degraded state that may be different from its historical conditions, although compatibility of restored ecosystems with local physiognomies is required (Table 1), whereas SER (2004) refers to any enhancement of a degraded ecosystem as rehabilitation. In Brazil, a rehabilitated ecosystem represents an ecosystem on its natural successional trajectory adapted to eventually changed environmental conditions. This ecosystem may be different from the ecosystem that occupied the area before the impact, but similar formations should be found within the region or water basin (Fig. 3). Brazilian legislation permits both restoration and rehabilitation after environmental impacts. Thus, evergreen forests may replace metalliferous savannas after mining in the Carajás Mineral Province in the Eastern Amazon.

Furthermore, legal norms specify criteria for the selection of species for rehabilitation purposes, the management of sites in environmental rehabilitation process and monitoring activities. Except for NVPL, all norms require the prioritization of native, autochthonous species, whereas non-native, non-invasive species may be allowed only in certain circumstances, e.g., after technical justification. Management strategies to control soil erosion, invasive species, fire, or other processes that potentially degrade the rehabilitation of restored sites are mandatory. Documents from IBAMA and ICMBio require that chemical inputs in restoration projects be kept to a minimum. Both normative instructions regulating PRAD elaboration require monitoring of revegetated areas every three or four years until rehabilitation goals have been achieved.

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[2] Presidential Decree no 8972 from January 23th, 2017, establishes the legal norm to install the National Politics for the Rehabilitation of Native Vegetation (Proveg from *Política Nacional de Recuperação Nativa*), which aims to rehabilitate 12 000 000 ha of degraded or altered areas, mainly pastures, until 2030. The Decree implements the National Plan for Rehabilitation of Native Vegetation (Planaveg from *Plano Nacional de Recuperação da Vegetação Nativa*) and places the National Committee for the Rehabilitation of Native Vegetation (Conaveg from *Comissão Nacional para Recuperação da Vegetação Nativa*) subordinate to the ministries of environment, agriculture, science, and finances. An overlap of competencies with institutions mentioned in the main text might generate additional conflicts and uncertainties that are not considered in this article.

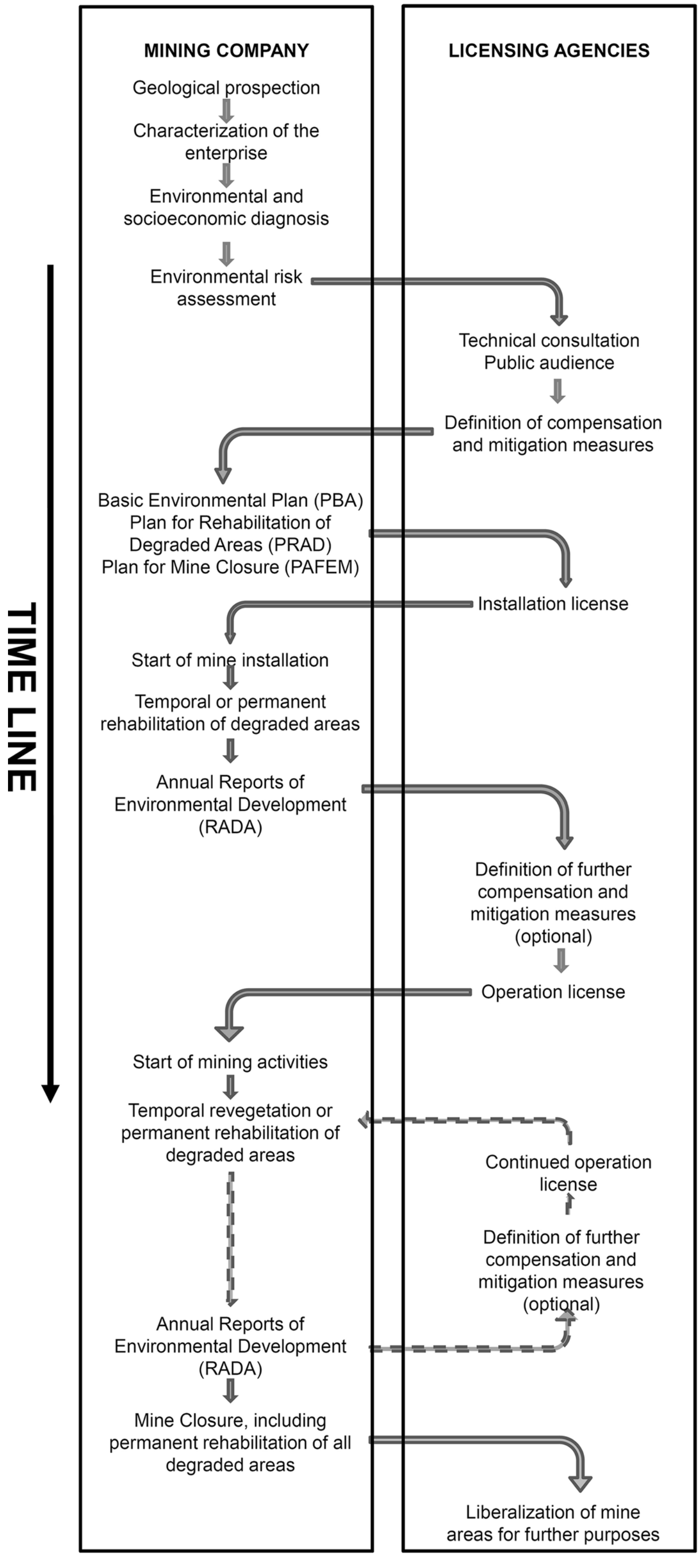

Fig. 2 Flowchart of the licensing process of mining operations in Brazil. Non-compliance of environmental liabilities leads to withdrawal of the license. The PBA (from Plano Básico Ambiental) presents all control measures and environmental programs to mitigate or compensate unavoidable impacts, whereas the PAFEM (from Plano de Fechamento de Mina) describes all obligatory measures to mitigate negative impacts for natural resources and society during and after mining activities. The RADA (from Relatório Anual de Desenvolvimento Ambiental) reports and updates all environmental and socioeconomic activities carried out by the mining operations. Social licenses as required in other countries (Gunningham et al. 2004) are dispensable in Brazil

Table 1 Comparison of different legal norms regulating the rehabilitation activities of degraded areas regarding their objectives, rehabilitation goals, definitions of important terms, permissions, requirements, and limitations of different management actions

	National Environmental Act (Law 9985, July 18th, 2000)	Presidential Decree no 5746 (April 5th, 2006)	Resolution CONAMA no 429 (February 28th, 2011)	Forest Code (Law 12 727, October 17th, 2012)	Normative Instruction IBAMA no 04 (April 13th, 2011)	Normative Instruction ICMBio no 11 (December 11th, 2014)	Presidential Decree no 8972 (January 24th, 2017)
Objective	Establishes criteria and standards for the launch and implementation of conservation units	Guidelines for the establishment of private natural heritage reserves	Guidelines for the voluntary rehabilitation of areas of permanent preservation (APP)	Norms for rural sustainable development and the protection of forests and other vegetation types	Establishes procedures for the elaboration, analysis, approval and monitoring of the implementation of rehabilitation projects for degraded or disturbed areas (PRAD)		Installation of national politics for the rehabilitation of 12 million hectares of native vegetation until 2030
Rehabilitation goal	Restore or rehabilitate the natural equilibrium, biological diversity and natural ecological processes of degraded ecosystems	Not defined	Rehabilitated physiognomies with the greatest compatibility with local physiognomies	Rehabilitation of forests and other physiognomies of native vegetation	Rehabilitation of ecosystems and their functions in the context of the water basin; achieve greatest compatibility with local physiognomies	Increase the diversity of spontaneous regeneration, increase the cover of native species, reduce or eliminate the cover of exotic invasive species	Forests and other physiognomies of native vegetation
Restoration	Restitution of a degraded ecosystem or a wild population as close as possible to its original condition	Not defined	Not defined	Not defined[a]	Restitution of a degraded ecosystem or a wild population as close as possible to its original condition		Human intervention in altered or degraded ecosystems to trigger, facilitate or accelerate natural succession
Rehabilitation	Restitution of a degraded ecosystem or wild population to a non-degraded state, which may be different from its original condition				Restitution of a degraded ecosystem or wild population to a non-degraded state, which may be different from its original condition		Restitution of native vegetation by implantation of agroforestry systems, natural regeneration, ecological rehabilitation, or restoration
Impacted/ altered area	Not defined				Area that maintained natural regeneration capacity after impact		Not defined[a]
Degraded area	Area unable to return by natural regeneration to an ecosystem that resembles the initial state				Area unable to return by natural regeneration to an ecosystem that resembles the initial state		
Natural species	Not defined		Species that present their natural populations within the limits of their geographic distribution		Not defined	Species that present their natural populations within the limits of their geographic distribution	
Exotic species			Any species outside its natural geographical range		Any species outside its natural geographical range as a result of accidental or intentional dispersal by human activities		
Invasive/ problematic species			Exotic species that threaten ecosystems, habitats or species and cause negative impacts		Exotic or native species that form populations outside their natural occurrence system or that exceed the desirable population size	Exotic species that produce changes in the natural ecological processes, threaten ecosystems, habitats or species, and cause negative environmental, economic, social or cultural impacts	
Methods	No comments	No comments	Plantation and sowing, natural regeneration and combinations, top soil application	Without specifications	Plantation and/or sowing, natural regeneration	Plantation and sowing, application of top soil, litter, vegetative propagation, natural regeneration	Without specifications

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Table 1 continued

	National Environmental Act (Law 9985, July 18th, 2000)	Presidential Decree no 5746 (April 5th, 2006)	Resolution CONAMA no 429 (February 28th, 2011)	Forest Code (Law 12 727, October 17th, 2012)	Normative Instruction IBAMA no 04 (April 13th, 2011)	Normative Instruction ICMBio no 11 (December 11th, 2014)	Presidential Decree no 8972 (January 24th, 2017)
Selection of species	No criteria	Native species	Native species that attract fauna, exotic species in exceptional circumstances (license necessary)	Up to 50% of planted trees may be exotic species	Species native to the region in which the recovery project will be inserted, adapted to local conditions, focus on endangered, zoochorous species	Native species should be preferred; non-invasive, exotic species may be applied after technical justification and outlining combat possibilities	No criteria
Management	No determination	No determination	Control and combat of erosion, invasive species, livestock, fire and other processes that cause degradation, protection of water resources	No determination	Control and combating of erosion, invasive species, livestock, fire and other processes that cause degradation, protection of water resources		No comment
Chemical inputs	No specification	No specification	No specification	No specification	Low-impact products for the control of or to combat invasive species	Reduced to a minimum	Without specification
Monitoring	No requirements	No requirements	No requirements	No requirements	Required for a period of 4 (8) years	Required for a period of 4 (8) years	No requirements

[a] Definitions of altered (area maintaining capacity of natural regeneration after impact) and degraded areas (areas modified by human impacts without capacity for natural regeneration) are given in Presidential Decree no 7830 from October 17th, 2012, regulating the Rural Environmental Cadastre System (SICAR from Sistema de Cadastro Ambiental Rural), which is referenced in Presidential Decree no 8972

RESTORATION TECHNIQUES AND CHALLENGES

Due to the parallels between successional and restoration chronosequences from simple to more complex communities, the ecological principles driving natural succession (Box 1) may guide the planning and execution of restoration activities (Christensen Jr. 2014). Restoration methods range from passive techniques, such as the removal of human disturbances, to active interventions, e.g., the plantation of seedlings, to accelerate the recovery of ecosystem structure and functioning (Morrison and Lindell 2011). Passive restoration depends on the arrival and establishment of spontaneous vegetation and fauna on the degraded site after the removal of human impact (DellaSala et al. 2003). Although this natural regeneration represents an economic alternative, passive restoration may be delayed in time, especially in areas isolated from larger remnants of natural vegetation or in dystrophic or compacted soils (Sartori 2015).

Active restoration methods are intended to accelerate the arrival and establishment of vegetation and fauna according to successional models (Walker et al. 2007). Nucleation is a technique of minimal interference; small nuclei are installed within degraded areas as starting points of ecosystem regeneration (Boanares and Azevedo 2014). Artificial shelters or perches to attract seed dispersing fauna or the installation of vegetation islands by the transposition of topsoil, seeds, branches, and/or whole plants might form nuclei (Vogel et al. 2015).

Active restoration approaches encompass plantations of selected seedlings or sowing of defined species mixtures to accelerate the formation of dense vegetation covers and the incorporation of biomass in the system (Elliott et al. 2013). Furthermore, soil preparation by liming and fertilization is intended to enhance plant growth (Carvalho et al. 2017). High-diversity plantations are thought to increase habitat heterogeneity for animal and plant recruitment (Rodrigues et al. 2009) and reproduce recurrent trajectories of natural succession (Matthews and Endress 2008). Important questions for planning active restoration strategies involve the selection and number of species to be planted or sown, planting or sowing densities, and criteria for the arrangement of seedlings in the field to achieve soil coverage in shortest time, considering low losses and costs (Rodrigues and Gandolfi 1996).

The choice of more passive or more active restoration techniques in the context of restoration depends on the intensity of land cover changes, the ecological resilience of the ecosystem to be restored, landscape context, and restoration goals (Holl and Aide 2011). Ecosystems differ in the rate at which they are able to recover naturally from human disturbances. Generally, the resilience of aquatic ecosystems is higher than that of forests (Elmqvist et al.

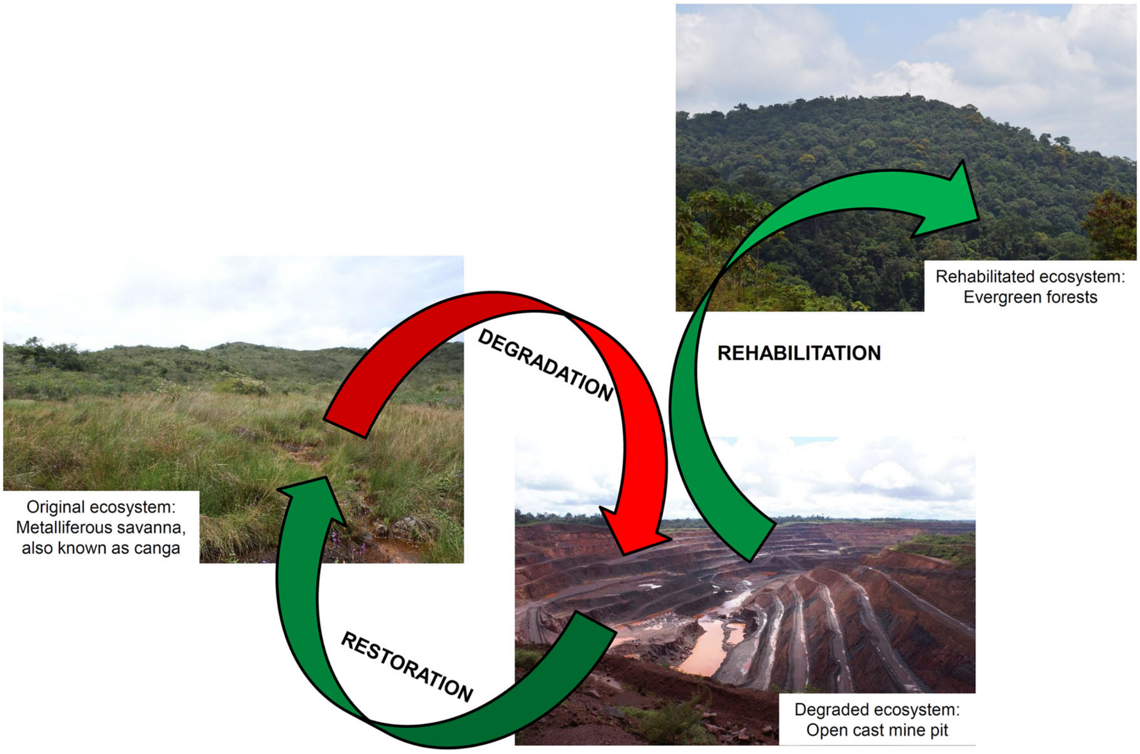

Fig. 3 The concept of degradation, restoration and rehabilitation in Brazilian legislation using an example from the Carajás Mineral Province, PA, Brazil. While restoration refers to the restitution of pre-disturbance ecosystems, i.e., cangas, as close as possible to its historic trajectories, rehabilitation is the restitution of a different ecosystem compatible with the region, such as the evergreen, semi-deciduous, or deciduous forest ecosystems found within the Carajás Mineral Province

2003). Furthermore, drier ecosystems show higher resilience due to a higher amount of wind-dispersed and resprouting species (Vieira and Scariot 2006). Nutrient availability and the concentration of toxic elements (e.g., Fe and Al) affect plant growth rates (e.g., Watanabe et al. 2006), thus influencing ecological resilience. Intrinsic site conditions, such as the distance to the nearest sources of seeds, limit the potential for passive restoration (Rodrigues et al. 2009; Sartori 2015).

Although experimental evidence is lacking for most ecosystems, Holl et al. (2013) considered active approaches to be more promising than passive strategies in the restoration of ecosystems (Scenario A in Fig. 4), especially when they are combined with the application of topsoil (Cristecu et al. 2012). In contrast, Brudvig (2011) highlights that over restoration, i.e., needless interventions, is able to reduce the ecosystem's intrinsic capacity to recover by natural trajectories (Scenario B in Fig. 4). As outlined in Box 1, natural trajectories of succession and floristic community composition are not always predictable (Suganuma and Durigan 2015). Thus, the application of standardized mixtures of seeds or seedlings may be insufficient, as restoration success relies on natural processes, such as the recovery of pollinator populations, arrival of seed dispersers and establishment of consumers and mycorrhizae (Brudvig 2011; Morrison and Lindell 2011; Peñe-Domene et al. 2014). Therefore, some experts recommend intermediate, e.g., nucleation, techniques as more powerful instruments for the restoration of degraded areas (Scenario C in Fig. 4). Although it is more time expensive, nucleation may trigger intermediate, natural restoration by allowing natural succession processes to dominate the recovery process (Corbin and Holl 2012; Holl et al. 2016). Nevertheless, scientific evidence for the better performance of nucleation techniques in a wide range of tropical ecosystems is lacking (Boanares and Azevedo 2014).

Due to profound alterations in geological, pedological, hydrological and topological conditions, especially during open-cast mining (Gastauer et al. 2018), the active restoration of mine land is frequently indicated to reduce a company's environmental liabilities. Nevertheless, expenses for restoration activities up to US-$60 000.00 per hectare, including topological reformulation, fertilization, liming, provision of native seeds, application of hydroseeding or biotextiles, highlight the environmental commitment of Brazilian mining companies.

Major challenges for the environmental restoration of mine land are the selection of fast-growing species adapted to the particular environmental constraints of mine land, biological invasions in sites undergoing revegetation and the lack of reproducible methods to measure the success of environmental restoration (Gastauer et al. 2018). The selection of promising species is handicapped by incomplete knowledge about the functional attributes of native flora in many regions of the world, including tropical Amazonia, and a lack of experience in the multiplication, reintroduction and management of promising species in the field (e.g., Carvalho et al. 2017).

Biological invasions occur when alien invasive plants, fungi, or animals that are not native to a specific location spread into ecosystems, reducing the abundance of native species and causing damage to ecosystem processes, the economy, or human health (Simberloff et al. 2013). Failed prevention, control or eradication methods are expensive and time consuming (Holden et al. 2016), requiring either the use of biological, sometimes non-native antagonists or chemical inputs (Simberloff 2009; Cordell et al. 2016). Furthermore, population control of alien invasive species is doomed to failure when propagule pressures from neighboring non-mining sites continue to increase (Catford et al. 2014).

The comparison of reference systems covered by natural vegetation and areas in environmental rehabilitation allow the evaluation of restoration success (Derhé et al. 2016). A variety of indicators, ranging from structural parameters, diversity indices, or modern ecological approaches, have been proposed for such monitoring activities (Gastauer et al. 2018), but no consensus has been achieved about what, when, and how to monitor (Kollmann et al. 2016). Therefore, Perring et al. (2016) postulated interdisciplinary approaches integrating soil sciences, genetics, and classic ecology and using a plurality of methods, such as vegetation and fauna surveys, functional and phylogenetic approaches, remote sensing, and metabarcoding techniques.

RESTORATION GOALS, GLOBAL CHANGES, AND NOVEL ECOSYSTEMS

Clearly formulated restoration goals, including target ecosystems, the number and extent of restored ecosystem functions and legal, social and economic requirements, increase the probability of achieving restoration success (Perring et al. 2016). The choice of more passive or more active restoration methods and the selection and propagation of species for rehabilitation purposes require estimation of the potential target of rehabilitation efforts (Skousen 2010). Although it is crucial to achieving success, an unambiguous definition is lacking in many restoration projects (e.g., Bernhardt et al. 2005). Focusing only on rapid greening of degraded areas instead of ecosystem functioning may stimulate the utilization of inappropriate species or techniques that compromise overall long-term restoration success. Therefore, a closer look at restoration goals is necessary.

While classic ecological restoration focuses solely on the restoration of ecosystem structure and functions to historical trajectories (Fig. 1, SER 2004), Higgs et al. (2014) recognized the position of restoration ecology on the interface between ecological and social systems and therefore considered the requirements of all involved actors, especially local people who depend on ecosystem services for their livelihood. Consequently, contemporary restoration projects show a plurality of goals, ranging from the restoration of tree or vegetation cover (e.g., Suganuma and Durigan 2015), conservation of threatened populations (Martin et al. 2015; Casazza et al. 2016), sequestration of carbon (e.g., Chazdon et al. 2016; Wheeler et al. 2016), and re-establishment of the full complement of species (Partel et al. 2011) to the

Box 1 Natural succession

Natural succession is the temporal sequence of distinct communities colonizing new habitats (primary succession) or habitats after disturbances (secondary succession). Generally, natural succession starts with communities containing a few species only, followed by community changes that increase diversity and complexity until it becomes stable and self-perpetuating as a climax community (Cowles 1899). Alterations in community composition, increases in species richness, and the diversity of plant and soil microbial communities or better fulfillment of ecosystem processes along successional gradients ranging from decades to centuries confirm this pattern for a variety of ecosystems (e.g., Jangid et al. 2013; Schrama et al. 2013).

According to Clements (1916), these sequences are highly deterministic and converge to stable climax conditions, independent of starting conditions. Gleason (1939), in contrast, emphasized the role of chance in the successional process, neglecting even the existence of a universal, climate-dependent climax. Although these extreme positions are now rarely endorsed, the importance of chance and determinism in natural succession has not been fully revealed, especially in megadiverse tropical ecosystems (e.g., Dini-Andrade et al. 2015). Consequently, there is no consensus about underlying mechanisms, i.e., the engine of succession causing transitions between communities. Instead, several hypotheses stressing ecological equivalence among species, differences in species' life histories (trade-offs, Laroche et al. 2016), different interspecific interactions ranging from facilitation to inhibition and/or resource ratios (Tilman 1985) compete as explanations of recurrent or non-recurrent community changes over time (Boukili and Chazdon 2017).

Once knowledge is achieved about the sequence of species along successional advances and the underlying ecological mechanisms that trigger them, the restoration of ecosystems may be achieved more effectively. Therefore, knowledge about the underlying processes of natural succession is crucial to optimizing revegetation and mine land restoration. Chase and Myers (2011) propose an approach to disentangle the relative importance of stochasticity and determinism in community assembly using β-diversity (Fig. 5), i.e., differences in community composition sensu Tuomisto (2010).

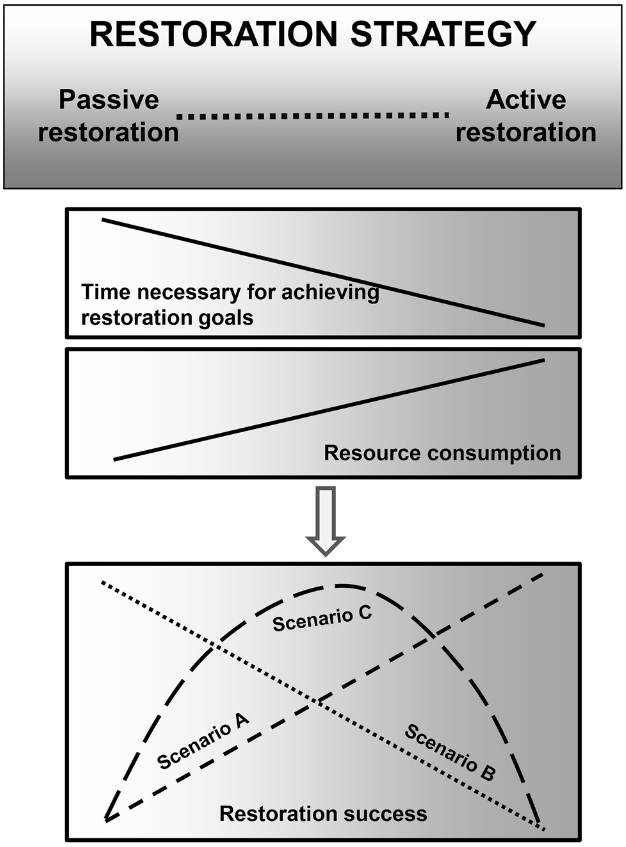

Fig. 4 Relationships between resource consumption and time necessary to achieve restoration goals and passive or active restoration approaches. Restoration success depends on whether higher input increases the restitution of biodiversity structure and functioning (Scenario A) or if active restoration leads to over restoration (Scenario B). Because the relationship between restoration success and restoration strategy is not straightforward, some authors suggest that intermediate restoration approaches are the most promising (Scenario C)

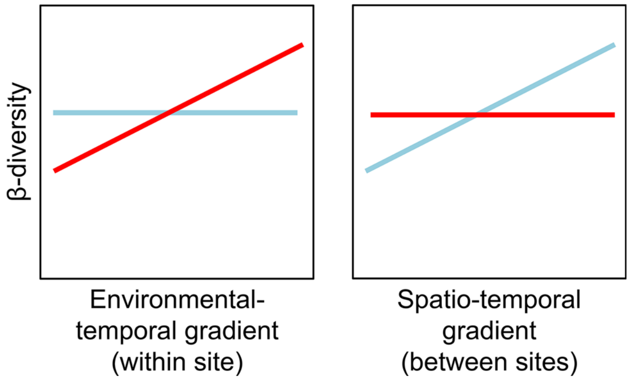

Fig. 5 β-Diversity, i.e., differences in community composition, within a site along an environmental-temporal gradient of successional advance (left) and along a spatio-temporal gradient between different sites, i.e., comparison of different stages from a successional chronosequence (right) assuming stochasticity (blue lines) or determinism (red lines) in community assembly. Under the assumption of complete stochasticity, β-diversity remains constant along a temporal gradient within a single site, although environmental alterations, such as the accumulation of nutrients, occur (blue line on left side). Furthermore, β-diversity increases along spatial gradients between different sites with the same environmental conditions, i.e., sites with similar stand ages, which were eventually compared in different periods (blue line on right side). In contrast, determinism causes constancy of β-diversity along spatio(-temporal) gradients and increases along environmental gradients (red lines). Adapted from Chase and Myers (2011)

provision of social (Mesquita et al. 2010) or educational opportunities (Cruz and Segura 2010). The aim of rehabilitation measures on contaminated sites may be the control or the removal of threats emanating from these sites (Pardo et al. 2017; Ye et al. 2017).

The definition of ecosystems' historical stages is not straightforward, as ecosystems have suffered different impact intensities during different historic periods of human occupation, such as different types of extractivism and traditional or industrial agriculture. As open-cast mines reshape entire landscapes (Paradella et al. 2015), the geological, pedological, hydrological, and topological conditions are completely different than their original conditions (Wang et al. 2016), and restoration or environmental rehabilitation may lead to the formation of natural ecosystems that are different from on-site or even nearby historical references. Furthermore, the rapid transformation of all ecosystems into new configurations without historical reference due to local and global changes impedes the return to historical trajectories (Corlett 2016). Land-use or climate changes may alter abiotic site conditions, thus shifting distributional ranges of extant species, which also causes biodiversity losses (e.g., Feeley and Selma 2016). Species extinctions in combination with biological invasions cause a homogenization of entire floras and faunas (Winter et al. 2009).

Hobbs et al. (2006) coined the terms 'hybrid' and 'novel ecosystems' for state alterations that impede the return to ecosystems' historical trajectories to advance the discussion about the influence of these global changes on restoration goals (Table 2). A consensus exists that partially restored, hybrid or novel ecosystems fulfill ecosystem functions and services, such as nutrient cycling, water regulation, or carbon sequestration (e.g., Morse et al. 2014). Non-native species may perform valuable functions in novel ecosystems, such as carbon sequestration or nutrient cycling (Hobbs et al. 2014; Muñoz-Erickson et al. 2014), showing high potential to control or combat alien invasive species (Cordell et al. 2016). Furthermore, the rehabilitation of ancient semi-natural ecosystems and consideration of climate change scenarios for conservation planning become prominent (e.g., Harris et al. 2006; Perry et al. 2015; Lu et al. 2017).

Table 2 Definition of different types of target ecosystems for environmental rehabilitation or ecological restoration of degraded mine lands. Adapted from Wagner et al. (2016)

Goal	Definition
Complete restoration	Return to full suite of structures and functions of pre-disturbed, on-site ecosystem; differences between historical and current state lie within their historic range of variation
Natural ecosystems without on-site reference	Return to full suite of structures and functions of pre-disturbed ecosystem originally present in further locations; differences between historical and current state lie within their historic range of variation
Hybrid ecosystems	Systems outside the historical range of variation due to the presence of non-native species interacting and forming assemblages not previously present; able to be returned to their historical trajectory with appropriate intervention, although the intervention may be technologically or economically impractical
Novel ecosystems	Systems distant from their historical range of variation due to on-site and off-site biotic, abiotic and functional changes, including prior contamination; retain very little of their historic characteristics; likely to be resistant to attempts to return them to their historical state and trajectory
Threat removal	Contamination and/or its remediation in ecologically unrestorable sites to avoid damage to neighboring sites

Although the existence of non-analogous ecosystems is widely recognized (Suding et al. 2004), this particular terminology risks considering undesirable outcomes of restoration projects as a consequence of factors beyond the influence of restorers, thus leading to a reduced overall restoration effort (Kattan et al. 2016). Miller and Bestelmeyer (2016) highlight that the inability to return to historical trajectories depends on multiple factors, such as costs and public support, and conclude that biotic and abiotic alterations in ecosystems are not alternate states but a choice. Nevertheless, they admit that novel ecosystems fulfill ecosystem services and contribute to the protection of biodiversity conservation (Lugo and Helmer 2004; Mascaro et al. 2008; Morse et al. 2014).

Ongoing discussions on the acceptance of hybrid and novel ecosystems indicate the need to involve a plurality of actors to define restoration goals and select activities to achieve biologically feasible, socioculturally acceptable, financially viable, and institutionally tractable rehabilitation and restoration projects. Considering the time scales of restoration processes, which may range from decades to centuries (Kondolf and Podolek 2011), multigenerational efforts are necessary (Richardson 2016). Due to the long-lasting consequences of short-term environmental rehabilitation and ecological restoration activities by single actors, such as mining companies, national or even international legislation should provide practical guidelines to optimize the governance of restoration and rehabilitation.

CONCLUDING REMARKS

As in global legislation, the definition of restoration goals and regulation of restoration activities are not straightforward in Brazilian legislation, although restoration ecology provides theoretical and practical frameworks to achieve biological feasibility, sociocultural acceptability, financial viability, and institutional tractability in the environmental rehabilitation of degraded mine lands. In contrast to US, Australian, and Indian laws (Richardson 2016), Brazilian restoration and rehabilitation legislation provides clear definitions regarding major terms in restoration ecology. Nevertheless, a clear statement about functions and the provision of ecosystem services encompassing structures guaranteeing biological feasibility is lacking within all extant legal Brazilian norms. Furthermore, modern, diversified, or plural restoration goals, such as educational or social purposes that are indispensable to achieving sociocultural acceptability, are not considered in Brazilian legislation.

Furthermore, the utilization of chemical inputs or non-native, non-invasive species may enhance the overall environmental restoration process. Fertilization may increase plant growth, thus contributing to faster achievement of restoration goals by reducing costs and time (Carvalho et al. 2017). Furthermore, selective application of herbicides or the use of non-native, non-invasive species might enable the control of undesired populations, such as ruderal or alien invasive species (Cordell et al. 2016). Thus, the application of such techniques within well-defined conditions should not be globally declined; rather, it should be considered on a case-by-case basis to achieve more effective environmental rehabilitation based on technical or scientific expertise. Furthermore, legal norms require the protection of rehabilitated or restored communities from fire, although fires of different intensity and frequency represent important components of many fire-prone ecosystems (e.g., Halofski et al. 2017).

Instead, legal norms regarding environmental restoration and rehabilitation of degraded areas postulate the compatibility of target ecosystems with local physiognomies. In practice, this assumption means that evergreen forests in the *Floresta Nacional de Carajás*, Parauapebas, Pará, Brazil, may substitute metallophyte savannas (Fig. 3) when a technical evaluation of pedological or hydrological conditions of rehabilitated ecosystems indicates such a shift. Nevertheless, ecosystems that are not present within the region, e.g., water basin, or hybrid or novel ecosystems are not allowed.

Mining environments, especially those resulting from open-cast mines, differ completely from historical on-site situations and may even lack natural references in the region. The complete alteration of abiotic conditions, especially geological substrates, topology and water regimes, may cause the emergence of novel ecosystems during mine land rehabilitation (Wang et al. 2016). Furthermore, external factors beyond mining companies' responsibilities, such as species extinctions, biological invasions, and shifts in species' distribution ranges due to climate or land-use changes, may impede ecosystem rehabilitation to historical trajectories (Hobbs et al. 2009). In such cases, novel ecosystems may represent more self-sustaining alternatives for mine lands than historical references, guaranteeing biological feasibility. Nevertheless, Brazilian environmental legislation does not allow the implementation of ecosystems that are incompatible with formerly present physiognomies, even though they might fulfill ecosystem processes and services in similar ways as their historic references (e.g., Lugo and Helmer 2004; Mascaro et al. 2008).

Where novel, non-historical ecosystems are not considered in national legislation but may represent appropriate outcomes for mine land rehabilitation, dialogues about their chances and risks involving all stakeholders are necessary to achieve public approval as well as juristic support (Richardson and Lefroy 2016). Therefore, we postulate discussions about restoration goals, including the target, eventually novel ecosystems, and the application of chemical inputs or non-native, non-invasive species in nations where environmental legislation is as restrictive as in Brazil (Martin 2017). Including controlling governmental agencies, mining companies, and representatives from society, such forums may be able to outline the responsibilities of mining companies and other land users regarding species extinctions, biological invasions, and further global changes to define compensation and mitigation measures for all stakeholders (Mansourian 2017). Furthermore, such thorough discussions addressing questions related to the restoration goals, including novel ecosystems, and the use of chemical inputs or non-native, non-invasive species within environmental rehabilitation projects, may achieve viability from a practical perspective and broad acceptance from a public and political perspective.

As long as broad agreements on these topics are lacking, effective mine land restoration may be constrained (Gastauer et al. 2018). In such cases, we recommend the inclusion of detailed, case-specific descriptions of emerging novel ecosystems due to difficulties related to producing self-perpetuating, resilient historical trajectories, and the use of non-native species, chemical inputs, and monitoring strategies within individual documents regulating rehabilitation provisions carried out by mining companies. Such documents, PRADs in the Brazilian legal setting, provide juristic support after their acceptance by licensing agencies. Furthermore, the sphere of responsibilities of the mining companies regarding biological invasions, species extinctions and further global changes may be outlined within these documents.

For dialogues on these topics, profound scientifically based knowledge about local natural ecosystems and the environmental conditions that let them emerge are indispensable tools. Research activities should encompass knowledge about the historical trajectories of ancient ecosystems and the environmental factors that impede their return during mine land rehabilitation. Additional research priorities include the comparison of different restoration methods and the development of effective monitoring strategies, including functional aspects that may contribute to the acceptance of emerging novel ecosystems.

Mining companies and public institutions together are responsible for pursuing scientific knowledge that, once available, enhances mine land rehabilitation, thereby contributing to more sustainable and more responsible mining (Gastauer et al. 2018). Constant surveying and mapping of non-native species in mining areas can rapidly detect the presence of new invaders and are necessary for risk assessments and the development of effective control mechanisms. While the systematic identification of the geological background and land-use changes in water basins affected by mining operations may help to precisely outline abiotic environmental shifts that may allow hybrid or novel ecosystems to emerge, meticulous descriptions of the sociological structures of local communities are indispensable for the definition of multiple rehabilitation goals. Developing propagation protocols for native species, investigating the influence of different substrates, determining the effects of micro- and macronutrient supplies on the growth patterns of potential species and testing different seed mixtures of native and non-native species for the revegetation of mining environments may guide the adoption of more effective rehabilitation technologies. Finally, scientific monitoring, e.g., the comparison of the floral, faunal, and microbial communities of rehabilitating and natural sites, and the development of straightforward bioindicators will aid in assessing the status of rehabilitation in reproducible ways, supporting transparency in all processes related to stakeholders.

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