Review Article
ISSN: 3041-556X
Journal homepage: https://er.researchfloor.org/

Revitalizing Degraded Rural Landscapes: Approaches and Strategies for Ecological Restoration

Bakhytzhan Yelikbayev[1], **Eduardo J. Azevedo Correa**[2], **Laith K. Al-Ani**[3], **Neimar F. Duarte**[4], **Marcela Claudia Pagano***[5]

[1] *Satpayev University, 22 Satpaev str., 050013, Almaty, Kazakhstan*
[2] *Empresa de Pesquisa Agropecuária de Minas Gerais, Campo Experimental de Pitangui, Caixa Postal 43, CEP 35650-000 Pitangui, MG, Brazil*
[3] *Instituto Federal de Minas Gerais, 30421-169 Belo Horizonte, Brazil*
[3] *Department of Plant Protection, College of Agriculture,University of Baghdad, Iraq and School of Biology Science, Universiti Sains Malaysia, 11800 Minden, Pulau Pinang, Malaysia*
[5] *Federal University of Minas Gerais, Belo Horizonte, Minas Gerais, Brazil*

Citation: Bakhytzhan Yelikbayev, Eduardo J. Azevedo Correa, Laith K. Al-Ani, Neimar F. Duarte, Marcela Claudia Pagano (2024). Revitalizing Degraded Rural Landscapes: Approaches and Strategies for Ecological Restoration. *Environmental Reports; an International Journal*. **DOI: https://doi.org/10.51470/ER.2024.6.2.23**

Corresponding Author: **Marcela Claudia Pagano** | E-Mail: **(marpagano@gmail.com)**

Received 10 September 2024 | Revised 23 October 2024 | Accepted 24 November 2024 | Available Online December 07 2024

ABSTRACT

To obtains table vegetal cover through the restoration of degraded ecosystems, attention to soil microbes and to the interactions between plants and microorganisms essential for better plant establishment. Since the understanding of natural regeneration or artificial plantations of vegetal communities together with advances in the study and use of mycorrhizas a common factor for restoration programs, new rehabilitation efforts have increased world wide. Most plant species are mycorrhizal including plantations of trees and grasses, which are degraded due to the increasing use of vegetation to fuel wood, and to agriculture and cattle. This study reviews current information on the restoration of degraded landscapes., mainly by conventional agriculture. Mechanisms through which restoration may be conducted are discussed as well as research necessary for the increased understanding of microbial benefits.

Keywords: *vegetation types, grassland, mycorrhizas, degraded areas, ecological restoration, soil reclamation*

Introduction

The benefits of restoring degraded landscapes through environmentally sustainable plantations and agroforestry systems are increasingly recognized worldwide. Plantations influence soil physical and chemical properties and modify soil microbiota, including both free-living and symbiotic fungal and bacterial populations. With the growing concerns of deforestation, afforestation, and the restoration of degraded ecosystems have gained significant importance [1–2]. Alongside these efforts, the valorization of biodiversity [3], soil seed banks [4–5], and soil microbes [6–7] has become a central focus in restoration ecology. Simultaneously, there has been a surge in research exploring the interactions between microorganisms and their associated plants in both undisturbed and degraded ecosystems [8–9]. Among these, studies on arbuscular mycorrhizas (AM) have proven particularly valuable. These symbiotic associations serve as indicators of ecosystem restoration in various conditions, providing critical insights for designing effective restoration programs. However, the potential of this symbiosis remains largely underutilized. Historically, ecological restoration efforts have been predominantly phytocentric, focusing on plants while often neglecting the critical role of belowground food webs [10–11] and soil ecology [12]. Furthermore, most restoration projects are short-term, limiting their capacity to assess essential processes such as plant growth, microbial dynamics, and long-term soil functionality [13].

Addressing these gaps requires a more integrated and long-term approach to restoration that considers the interplay between plants, soil microbiota, and eco system processes.

The current restoration practices present disadvantages such as inadequation for preserving wild plant species with small populations [14]. Moreover, modification of conservation and restoration laws need more scientific evidence. Restoration will also deal with the conservation and reintroduction of rare and endangered plants, which are essential for ecological, economic, and human health, being a major focus for international conservation of biodiversity and restoration ecology [15]. Using mono cultures off ruited native species having propagules dispersed by wildlife contribute to more proper environmental conditions for native fauna preservation. Mono culture plantations of high-value native timber species were tested in many countries[16]. Benefits of maintaining tree diversity in forestation to enhance the conservation of trees and, also, other organisms and to increase natural forest regeneration, a long-term process that can take a century or more [17]. However, values of forest products may be improved or not. A disadvantage is the difficult management; thus, scientific information on few studied species and compilation of mixture plantations are needed[18].

Conservation efforts suggests effective strategies to preserve the regional biodiversity, including threatened and highly endemic species, unique habitats, special landscape characteristics, ecosystem processes, and services [19].

Priority Areas for conservation maps are utilized for choice actions for the creation of Protected Areas and for habitat restoration [20]. Moreover, habitat indicators relevant for forest have not been identified. We explore the current information on ecosystem´s restoration, with respect to the worldwide research, focusing on the benefits of AM symbioses. Possible mechanisms through which restoration may operate as well as research paths that are necessary for the increased understating of mycorrhizal benefits are discussed. Furthermore, reports from South America are emphasized.

Ecological Restoration

There is a need for more scientific information on forest restoration practices of specific sites and strategic priority areas in tropical biomes considering the urgent demand for their forest repairing. [21] have discussed the state of art of ecological restoration in Brazil. Not to mention the approach by [22] to compare restored sites with two or more reference sites (**Figure 1**) to better interpret the variation that occurs in ecosystems. Necessities of reference sites to evaluate restoration success are considered necessary. In this sense, most scientific reports commonly include only one reference site. However, researchers continue to debate on the effective specific techniques, laws and regulations for ecological restoration. With regard to natural regeneration in degraded tropical forests, it was stressed the proliferation of pioneer plants and fall of the shade-tolerant/old-growth woody plants in a number of neotropical fragmented forest land scapes. In this sense, the increase of disturbance-adapted native organisms, such as pioneer tree species, has a key role in tropical biodiversity of fragmented land scapes [13].

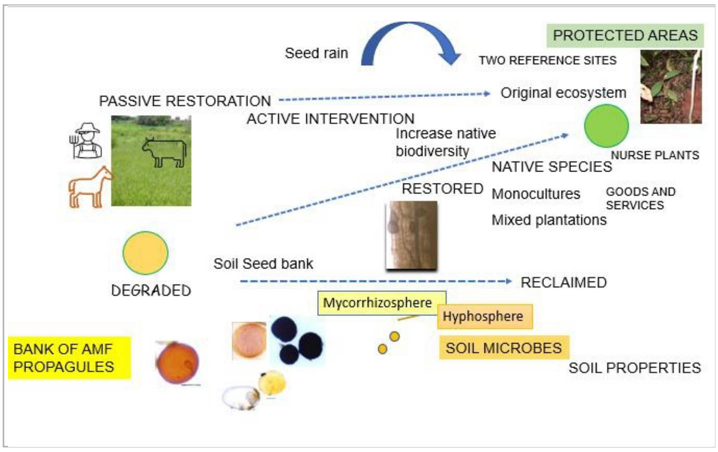

Figure 1. A conceptual diagram of ecosystem restoration can illustrate changes in forest cover within a landscape over time, driven by agricultural intensification. The diagram depicts forest cover as a solid line, highlighting its decline due to deforestation and agricultural expansion, followed by gradual recovery through restoration efforts.

For native species, it was recently shown that wider spacing of planting increased initial growth of six plant species (*Anadenanthera macrocarpa* Benth. Brenan, *Schinus terebinthifolius* Raddi, *Schizolobium parahyba* Blake, *Chorisia speciosa, Cordia* sp.and *Inga marginata*) in plantations of forest at the Guandú River Basin, Brazil[23-24]. However, studies on tree species used in forest recovery are in cipient and little is known about the characteristics of growth of Brazilian native species (Pagano and Araújo 2011). In Brazil, the selection of fast-growing legume trees and their preferential mycorrhizal and specific rhizobial symbioses [25] has resulted in successful indication of many legumes for revegetation and restoration[26].

With regard to riparian sites, which deserve urgent conservation, restoration of sugarcane degraded lands through plantations of high-diversity native tree species (Rodrigues et al. 2011). Those fragmented sites presented low resilience, limiting the potential for autogenic restoration, therefore the biologically viable restored forests provide persistent biodiversity. Additionally, [27-28] compiled information on AM in native and restored riparian sites in Brazil, demonstrating the importance of this association as a strategy to recovery riparian ecosystems. Moreover, the soil aggregation is also an important factor to be evaluated in restoration approaches as the stability of soil macro aggregates is highly dependent on the growth and decomposition of roots and mycorrhizal hyphae, which are the most important mediator of soilaggregation[29]. Moreover, to preserve free flowing rivers, rewilding of watercourses and removing of dams were proposed[30]. Soil health indicator measurements such as soil organic matter (SOM), soil organic carbon (SOC), soil test nutrients, and soil microbial community size or relative abundance with regard to exotic species, reports from South America showed interest in reforestation with *Eucalyptus* plantations as an alternative cover vegetation for degraded soils at the Pampa, Argentina [31]. However, the use of mixed plantations such as agroforestry systems with eucalypt and local native species can provide wood supply for local communities [32] or food, forage and N to the soil (for habitat, shade and soil quality enhancement [33]. Multipurpose trees, particularly leguminous species, play a crucial role in ecosystem restoration. However, many pioneer or fast-growing species suitable for the early stages of forest or temperate grassland restoration remain unidentified or are not well-suited for tropical and subtropical grasslands. Most restoration studies rely on fast-growing, short-lived species for initial cover, followed by perennial plants in later stages [34]. While effective in the short term, these species may inhibit the establishment of perennial plants in subsequent phases [35].

Introducing pioneer species can be beneficial in areas dominated by invasive species or prone to soil erosion, though the long-term impacts of this practice on biodiversity require further investigation. Alternatively, restoring small, slow-growing species to facilitate colonization by native species and increase overall species richness may be a more sustainable strategy [36]. Trait-based approaches, particularly for grasses and forbs, could further enhance restoration efforts by addressing the functional roles of herbaceous species.

Additionally, a better understanding of the interactions among vegetation, fauna, soil microbiota, and soil properties is critical for effective restoration. For instance, soil microbes [38], ants [39], and large herbivores, including farm animals [40–41], play significant roles in shaping ecosystems. Nurse plants [42] are particularly valuable for facilitating the establishment and persistence of plant species [43]. Identifying key ecological engineers—organisms that maximize plant establishment—is another essential aspect of restoration that remains largely unexplored.

Restoration efforts can also be significantly improved by reintroducing mycorrhizal fungi from native plant microbiomes. This has shown promise, especially in temperate grassy ecosystems [44]. A comprehensive discussion on the state of ecological restoration in Brazil highlights these strategies and their potential applications [45].

Plantations are essential not only for providing goods and services, such as timber, but also for delivering a broader range of ecological benefits compared to traditional industrial timber plantations [46]. By prioritizing strategies that enhance financial returns—such as the production of high-quality wood—while also addressing multiple objectives, plantations can contribute to sustainable development. Implementing these diverse approaches across various locations within a landscape mosaic can maximize both economic and ecological outcomes.

Soil Microbiota In Ecological Restoration

[47] highlighted the potential of soil amendments, including compost, biochar, and arbuscular mycorrhizal (AM) fungi, for restoring disturbed sites while critiquing the predominance of the phytocentric model during that time. However, the rhizosphere—a "hot spot" of microbial activity that bridges plants and soil microbiota—must not be overlooked in rehabilitation efforts. For successful forest restoration in arid regions, it is crucial to recognize that most trees form mycorrhizal associations. AM fungi have been shown to support both terrestrial and aquatic plants [49], with many species in natural ecosystems relying significantly on these symbiotic relationships [50]. This makes AM fungi invaluable for ecological restoration and the conservation of natural ecosystems.

AM fungi contribute to increased uptake of phosphorus (P), nitrogen, and other essential nutrients by plants [51]. Beyond these nutritional benefits, recent research has focused on their non-nutritional effects, such as reducing plant diseases, modifying water relationships [52–53], and stabilizing soil structure [54]. Since AM fungi are highly specialized to both biotic and abiotic environments [55], studying soil properties alongside plant species composition is essential for maximizing their benefits in restoration projects.

Furthermore, recent studies have revealed that AM fungi can enhance soil resistance to wind erosion, even without directly increasing plant growth [56]. While AM fungi were initially valued in restoration for their ability to promote plant growth [57], recent attention has shifted to their role in soil structure stabilization and erosion control. Their involvement in soil aggregate stabilization, both physically and chemically, has become a key area of interest. The extraradical hyphae of AM fungi enmesh soil and root particles, producing proteins like glomalin, which play a critical role in stabilizing soil aggregates [58, 60], improving the management of AM fungi in field situations remains an urgent priority. Harnessing their full potential requires a deeper understanding of their interactions with soil and plant systems to achieve meaningful outcomes in restoration projects.

Both biotic factors (such as disease, herbivory, and the presence of competitors) and abiotic stresses (including nutrient deficiency and drought) can significantly impact the fitness of both plants and soil microorganisms. Since soil microorganisms are highly influenced by abiotic conditions like soil type and water content, conducting comprehensive soil analyses is essential to predict their establishment and design effective long-term interactions. Implementing diagnostic procedures to identify and mitigate anthropogenic disturbances in degraded sites is a critical first step [61].

Subsequent actions should focus on soil characterization and improvement, as well as managing invasive species, weeds, leaf-cutter ants, and problematic grazer fauna—such as capybara in Brazil—to ensure restoration success.

Native plants, which are generally more mycotrophic (reliant on mycorrhizal associations) than weeds, play a key role in restoration efforts. However, in some cases, arbuscular mycorrhizal fungi (AMF) can also promote plant growth in certain mycotrophic weed species [62–63].

Diagnostic protocols are essential for identifying barriers to ecological succession and designing effective restoration strategies. For example, in sugarcane-degraded soils of Brazil, a stepwise approach has been proposed to assess site suitability for restoration. This includes evaluating the micro-site conditions for native plant establishment and growth, identifying barriers such as soil degradation, aggressive exotic grasses, intense herbivory, and seed predation, and examining the presence and viability of soil seed banks along with the cohort of sprouts, seedlings, and saplings of native tree and shrub species. Additionally, analyzing the relative abundance of different life forms, such as herbs, shrubs, and trees, as well as successional groups like pioneer and non-pioneer species, is crucial. The presence of adjacent forest fragments and their effectiveness in providing seed rain is another important factor to consider. Furthermore, incorporating diverse plant functional groups and symbioses, such as mycorrhizal associations and rhizobia, is critical for developing sustainable restoration practices. The use of carefully selected rhizobia strains and isolates of arbuscular mycorrhizal (AM) fungi has been shown to enhance plant growth, seedling survival, and rhizospheric interactions. Among these, plant survival remains a key parameter for selecting species with high potential for restoration success [64].

Grassy biomes

The restoration of biodiverse tropical and subtropical grassy ecosystems, such as grasslands and savannas, remains a challenging task. Proper management practices, including the regulation of livestock and wild herbivores, tree cutting and shrub removal, control of invasive species, and the reintroduction of native grasses and forbs through seeding or transplantation, are essential for the effective restoration of these ecosystems [65]. Unfortunately, grassy biomes have often been overlooked in conservation goals, and this neglect stems from confusion regarding their ecology, conservation value, distribution, and historical significance.

While many ecosystems within grassy biomes may benefit from ecological restoration, the restoration strategies proposed by the World Resources Institute (WRI) [2] are not always aligned with the needs of grassland biodiversity. Furthermore, the WRI's deforestation map, which identifies areas suitable for restoration, fails to recognize agricultural lands within deforested landscapes as potential restoration opportunities [2]. The economic value of agricultural lands makes them difficult and costly to reforest. Attempts to offset agricultural deforestation by pursuing afforestation in grassy biomes may inadvertently exacerbate biodiversity losses and further degrade ecosystem services.

The "Forest and Landscape Restoration Opportunities" map, produced by WRI and supported by prominent scientific and environmental organizations, has gained legitimacy within conservation circles. However, it remains critical to question whether its proposed solutions, including afforestation efforts, adequately address the complexity of ecosystem restoration, particularly in biodiverse grassy biomes. WRI's collaboration with the International Union for the Conservation of Nature, the Global Partnership on Forest and Landscape Restoration, and other environmental organizations has shaped the map's credibility [66-68].

Figure 2 outlines the steps for adding AM fungi to disturbed soils where native AMF is absent or minimal. The most effective method is to inoculate the restoration site with topsoil, which contains native AMF propagules, organic matter, and seeds. If topsoil is unavailable, commercial inoculants, typically containing a single species like *Glomus intraradices*, can be used, though developing site-specific AMF inocula is preferable. Monitoring of the restored site involves evaluating infective propagules, spore abundance, and root colonization percentage. Statistical analyses, such as dendrograms from cluster analysis, can assess restoration progress.

Studies have shown that plant species intolerant to climate change should be avoided for long-term restoration. AMF and rhizobial inoculation can reduce stress from allelopathic chemicals in species like *Eucalyptus camaldulensis*, with native plants like *A. peregrina* thriving under inoculation. Additionally, AMF and ectomycorrhizae can associate with *E. camaldulensis* [69, 70].

In riparian forest restoration in Brazil, efficient rhizobial strains were selected for inoculating native species *Inga edulis*, *Mimosa bimucronata*, and *Centrolobium tomentosum*. The AMF species used for inoculation included *Acaulospora scrobiculata*, *Gigaspora margarita*, *Glomus brohultii*, and *Scutellospora cerradensis*. Double inoculation was found to enhance the survival of these species. Additionally, three AMF families were identified in the rhizosphere soils.

The procedure for using AMF in ecosystem restoration involves several steps. First, a diagnostic evaluation of the degraded site is conducted (a). Then, two or more undisturbed reference sites are established (b). Restoration is achieved by introducing topsoil or plantations, followed by AMF inoculation on host plants or by inoculating healthy soil (c). Monitoring the restored sites includes determining infective propagules, such as spores recovered from rhizospheric soils (d) and roots of plants stained for AM colonization in both degraded and reference soils (e) (Photos by M. Pagano).

Interestingly, in arid regions, the introduction of AM fungi has improved restoration efforts through the use of plantations [71]. In dry deciduous woodlands, such as those in Northern Ethiopia [72-73], most trees form associations with mycorrhizas (Fig. 2), highlighting their importance for restoration projects. Similarly, in Brazil, [74] demonstrated the presence of AM fungi across different successional stages in a tropical dry forest. However, the formation of AM was found to be more closely linked to the physicochemical characteristics of the soil and the development of the host plant, rather than the specific successional stage.

The multiple symbiosis of AM fungus and rhizobium in restoration and revegetation

AM fungi can enhance N2-fixing symbioses by providing phosphorus, boosting nitrogen fixation and promoting efficient soil reclamation and ecological restoration [75]. Compatibility between native rhizobial strains and AM species can be tested in controlled conditions [76]. The role of native plantations and reduced fertilization in the presence of symbionts requires further study. Agroforestry, which incorporates legume trees supporting rhizobia and AM, plays a vital role in maintaining soil fertility [77]. Eucalyptus species, due to their growth rate and adaptability, alongside microbiological inoculants, are increasingly studied for afforestation and revegetation projects [79-80]. The choice of plant species is critical for managing and conserving mycorrhizal species, and the loss of native AM fungi due to disturbance requires more management.

Particularly interest on riparian restoration has revealed AM as an important and rich component [16] that should be included in restoration programs. This is where detailed works are invaluable; and will provide important evidence of the fungal and plant diversity association.Figure 3 shows tree plantations associated with mycorrhizas in riparian forests of Brazil and AMF spores recovered from their rhizospheric soils.Thus, restoration specialists have started inoculating AM to degraded soils with the objective of promoting plant growth, accelerating ecological succession, or attain desired plantations [16] For example, [45] reported the successfulrestoration of a dam removal (soil consisted in fine sediment mixture) in USA with inoculatednative plant species and mulch (sawdust with alder chips inoculated with the saprophytic fungus).As restoration efforts require a better understanding of successional processes (Quesada et al. 2009), the soil microbiota succession must also be studied. With regard to AMF and ecological succession, there is controversial reports. [18] have discussed the state of art of ecological restoration in Brazil.In Brazil, [13] has showed that the AM root colonization of native trees decreased with the advance of ecological succession. Opposite, early successional plant species present higher root colonization and response to inoculation. He suggests a decrease in use of AM for nutrient acquisition in late successional groups. This agrees with the ecological theory, as fast growth pioneer species will need fast nutrient translocation. On the other hand, in other studies the mycorrhizal plant species (AM species) were mature forest trees [13-14] have analyzed this topic and pointed out that there are few field studies as well as few studies at the seedling stage. They showed that there is no specific beneficial relationship between late-seral AM inoculaand late-seral tree species.[19] compiled ecosystems services in tropical zones. They listed the production of food, wood, fibres and the purification of water, and regulation provision degrading physical chemical illuviation – as well as cultural recreational services.

AM colonization was evident in all plant roots collected at the land covers studied (Table. 1).

Aseptate intra- and intercellular hyphae, along with vesicles, were the most common AM structures observed in plant samples. Arbuscules and hyphal coils were less frequent. Root colonization was highest in the revegetated (77%) and preserved areas (66%), compared to the degraded area (58-60%). In the preserved area, high colonization was associated with abundant arbuscules but low vesicle presence (10%). The mycorrhizal status of herbs from families like Asteraceae, Lamiaceae, Malvaceae, and Poaceae in riparian vegetation showed Arum-type colonization, which was dominant in all areas. This type is common in plants that grow in sunlight and spread faster than the Paris-type, which was found in a few Poaceae species in the preserved area. AM spore density was higher in the degraded area, and 14 AM species were identified, with the preserved area having the highest fungal diversity. Scutellospora species were found in the degraded area, but no Gigaspora species were present there.

Table 1 Some papers dealing ecological restoration

Reports on AMF and plant restoration	Country	References
Grassland Restoration	North America	Middleton and Bever (2012)
Restored environments	Argentina, Brazil, North America	Pagano (2012)
Riparian forest	Brazil	Braghirolli et al. (2012)Pagano et al.2021
Mine spoilrestoration	Brazil	Souza et al. (2011)
AMF in degraded land restoration	Brazil	Soares and Carneiro (2010)
Restoration of semiarid vegetation	Mexico	Monroy-Ata and García-Sánchez (2002)
Restoration of mycorrhizae on disturbed lands	USA	Allen (1991)

Figure 2. Vegetation associated with mycorrhizas in semiaridforestsof Brazil and AMFspores recovered from rhizospheric soils. Clockwise, from upper: native vegetation, spores (*Scutellospora*and*Acaulospora*) recovered from rhizospheric soils (photos by M. Pagano)

Figure 3. Trees associated with mycorrhizas in forests. Clockwise, from upper left: native tree plantation, colonized root by AM, and spores recovered from rhizospheric soils:*Scutellospora* and *Acaulospora*(photos by M. Pagano)

Conclusions

Environmental changes can impact plant-soil-associated microorganisms in terms of their number, diversity, or activity. Restoration practices, however, help minimize soil disturbance, increase organic matter, and improve soil structure to support soil communities linked to native plant species. Mycorrhizas, along with Rhizobium, are crucial for plant health, particularly under stressful conditions. Efforts to harness the benefits of mycorrhizae for restoration have been reported, aiming to better understand soil microorganisms and their roles during plant succession. Further research is needed on the use of plantations for restoring degraded sites, especially in riparian, dry forest, and other threatened ecosystems.

REFERENCES

1. Albrecht, M.A., Guerrant E.O., Maschinski J., Kennedy, K.L. 2011. A long-term view of rare plant reintroduction. Biological Conservation, 144, 2557–2558.

2. Allen, M.F. 1991. The Ecology of Mycorrhizae. Cambridge University Press, New York, NY. 184 p.

3. Aronson, J.,Brancalion, P. H. S.,Durigan, G.,Rodrigues, R. R., Engel, V. L. et al. 2011. What Role Should Government Regulation Play in Ecological. Restoration? Ongoing Debate in São Paulo State, Brazil.Restoration Ecology, 19, 6, 690–695.

4. Bilalis, D., Karkanis, A., Konstantas, A., Patsiali, S., Triantafyllidis, V. 2011. Arbuscular mycorrhizal fungi: a blessing or a curse for weed management in organic olive crops? Australian Journal of Crop Science, 5, 7, 858-864.

5. Braghirolli, F.L., Sgrott A.F., Pescador R., Uhlmann A., Stürmer, S.L. 2012. Arbuscular Mycorrhizal Fungi in Riparian Forest Restoration and Soil Carbon Fixation. R. Bras. Ci. Solo, 36, 733-743.

6. Bakker, J.P., Bakker, E.S., Rosén, E., Verweij, G.L., Bekker, R. 1996. Perspectives of restoration of species-rich dry alvar grassland from the seed bank after *Juniperus* encroachment. J. Veg. Sci. 7, 165-176.

7. Birhane, E., Kuyper, T.W., Stercka, F.J., Bongers, F.2010. Arbuscular mycorrhizal associations in *Boswellia papyrifera* (frankincense-tree) dominated dry deciduous woodlands of Northern Ethiopia. Forest Ecology and Management, 260, 2160–2169.

8. Borie, F., Rubio, R., Rouanet, J.L., Morales, A., Borie, G., Rojas, C. 2006. Effects of tillage systems on soil characteristics, glomalinand mycorrhizal propagules in a Chilean Ultisol. Soil & Tillage Research. 88, 253–261.

9. Brockerhoff, E.G., Jactel, H., Parrotta, J. A., Quine, C. P., Sayer, J. 2008. Plantation forests and biodiversity: oxymoron or opportunity? Biodiversity and Conservation, 17, 925–951.

10. Buisson, A Fidelis, Gerhard E. Overbeck, I. B. Schmidt , G Durigan , T. P. Young , Swanni T. Alvarado , André J. Arruda, Sylvain Boisson , William Bond10, A et al. A research agenda for the restoration of tropical and subtropical grasslands and savannas 2020 Restoration Ecology

11. Burri, K., Gromke,C., Graf, F. 2011. Mycorrhizal Fungi Protect The Soil From Wind Erosion: A Wind Tunnel Study. Land Degradation & Development. DOI: 10.1002/ldr.1136.

12. Callaham, M., Rhoades, C. R., Heneghan, L. 2008. A striking profile: soils knowledge in restoration management and science. Restoration Ecology, 16, 604–607.

13. Cardoso, I.M.,Kuyper, T.W. 2006. Mycorrhizas and tropical soil fertility. Agric. Ecosyst. Environ., 116,72–84.

14. Carrenho, R.,Barbosa, F.F.,Araújo, C.V.M.,Alves, L.J., Santos, O.M. 2008.Mycorrhizal Associations in *Eucalyptus* spp.: Status and Needs. Tree and Forestry Science and Biotechnology, 2, 1.

15. Chaer, G. M., Resende, A.S., Campello, E.F.C., de Faria,S.M.,Boddey, R.M. 2011. Nitrogen-fixing legume tree species for the reclamation of severelydegraded lands in Brazil**.** Tree Physiology, 31, 139–149.

16. Chaudhary, B., Griswold, M.2001. Mycorrhizal Fungi - A Restoration Practitioner's Point of View. Ecesis, Newsletter of the California Society for Ecological Restoration – SERCAL. p. 4.

17. Chazdon, R.L. 2008. Beyond deforestation: Restoring forests and ecosystem services on degraded lands. Science, 320, 1458–1460.

18. Choi, Y.D., Temperton, V.M., Allen, E.B., Grootjans, A.P., Halassy, M., Hobbs, R.J., Naeth, M.A., Torok, K. 2008. Ecological restoration for future sustainability in a changing environment. Ecoscience, 15, 53–64.

19. Cook, K. L., Wallender, W.W., Bledsoe, C. S., Pasternack, G., Upadhyaya, S. K. 2012. Effects of native plant species, mycorrhizal inoculum, and mulch on restoration of reservoirsediment following dam removal, Elwha River, Olympic Peninsula, Washington. Restoration Ecology, 19, 2, 251–260.

20. Covacevich, F., Berbara, R.L.L.2011. Indigenous arbuscular mycorrhizae in areas with different successional stages at a tropical dry forest biome in Brazil.African Journal of Microbiology Research, 6, 27, 5523–5535.

21. de Faria, S.M., E.F. Campello, D.F. Xavier and R.M. Boddey. 2010. Multi-purpose fast-growing legume trees for smallholders in the tropics and sub-tropics: firewood, fencing and fodder. In:Comunicado Técnico. EmbrapaAgrobiologia, Seropédica. 6 p. http://www.cnpab.embrapa.br/publicacoes/download/cot127.pdf

22. Fonseca ,C.R. E. M. Venticinque Biodiversity conservation gaps in Brazil: A role for systematic conservation planningPerspectives in Ecology and Conservation 16, 2, 2018, 61-67.

23. Gomes, M. P., Carvalho, M., Marques, T. C. L. L. S. M., Duarte, D. M., Nogueira, C. O. G.,Soares, Â. M., Garcia, Q. S. 2012. Arsenic-Sensitivity in *Anadenanthera Peregrina* due to arsenic-induced lipid peroxidation. International Journal of Applied Science and Technology, 2, 2, 55–63.

24. FAO. 2011. The state of forest resources – a regional analysis, Food And Agriculture Organization Of The United NationsRome. In: *State of the World's Forests,pp. 27.*

25. Fitter, A.H., Heinemeyer, A., Husband, R., Olsen, E., Ridgway, K.P., Staddon,P.L. 2004. Global environmental change and the biology ofarbuscular mycorrhizas: gaps and challenges. Can. J. Bot.,82, 1133–1139.

26. Frioni, L.,Minasian, H.,Volfovicz, R. 1999. Arbuscular mycorrhizae and ectomycorrhizae in native tree legumes in Uruguay. For. Ecol. Manage, 115, 41-47.

27. Giménez, J.E., Salerno, M., Hurtado, I. 2002. Rehabilitation of desurfaced soils by afforestation in La Plata County, Argentina. Land Degrad. Develop., 13, 68–77.

28. Gomes, M. P., Carvalho, M., Marques, T. C. L. L. S. M., Duarte, D. M., Nogueira, C. O. G., Soares, Â. M., Garcia, Q. S. 2012. Arsenic-Sensitivity in *Anadenanthera Peregrina* due to arsenic-induced lipid peroxidation. International Journal of Applied Science and Technology, 2, 2, 55–63.

29. Guedes B. S., B. A. Olsson; SitoeA. A. Egnell G. Net primary production in plantations of Pinustaeda and *Eucalyptuscloeziana* compared with a mountain miombo woodland in Mozambique. Global Ecology and Conservation 15 (2018) e004142

30. Harris, J. 2009. Soil Microbial Communities and Restoration Ecology: Facilitators or Followers? Science, 325, 573–574.

31. Heneghan, L., Miller, S.P., Baer, S., Callaham, Jr. M.A., Montgomery, J., Pavao-Zuckerman, M., Rhoades, C. C., Richardson, S. 2008. Integrating Soil Ecological Knowledge into Restoration Management. Restor. Ecol., 16, 608–617.

32. Huante, P., rincón, E. Allen, E.B. 1993. Effect of vesicular-arbuscular mycorrhizae on seedling growth of four tree species from the tropical deciduous forest of Mexico. Mycorrhiza, 2, 141–145.

33. Janos, D.P. 1980. Mycorrhizae influence tropical succession, Biotropica,12, 56–64.

34. Kardol, P., Wardle, D.A. 2010. How understanding aboveground-belowground linkages can assist restoration ecology. –Trends in Ecology and Evolution, 25,670679.

35. Larjavaara A Review on Benefits and Disadvantages of Tree Diversity. M. The Open Forest Science Journal, 2008, 1, 24-26

36. Lamb,D., Erskine P. D. Parrotta., J. A. Restoration of Degraded Tropical Forest Landscapes2005, 310 SCIENCE, 1629-1632 www.sciencemag.org

37. Margules, C.R. Pressey R.L. Systematic conservation planning. Nature, 405 (2000), 243–253.doi: 10.1098/rstb.2016.0329.

38. Lehmann, C E R , Parr C L P. 2016. Tropical grassy biomes: linking ecology, human use and conservationPhilos Trans R Soc Lond B Biol Sci. 2016, 19;371(1703):20160329, Philos Trans R Soc Lond B Biol Sci2016 Sep 19;371(1703):20160329.

39. Matias, S.R., Pagano, M.C., Muzzi, F.C., Oliveira, C.A., Carneiro, A.A., As, N.H., Scotti, M.R. 2009. Effect of rhizobia, mycorrhizal fungi and phosphate-solubilizing microorganisms in the rhizosphere of native plants used to recover an iron ore area in Brazil. European Journal of Soil Biology, 45, 3, 259–266.

40. Mathur, N., Vyas, A., 2000. Influence of arbuscular mycorrhizae on biomass production, nutrient uptake and physiological changes in *Ziziphus mauritana* Lam. under water stress. Journal of Arid Environments, 45,191–195.

41. Middleton E. L., Bever J. D. 2012. Inoculation with a Native Soil Community AdvancesSuccession in a Grassland Restoration. Restoration Ecology, 20, 2, 218–226.

42. Monroy-Ata, A., García-Sánchez, R. 2002. Mycorrhizal fungi of arid and semiarid ecosystems. The National Autonomous University of Mexico (UNAM), Mexico City. 97 p.

43. Nannipieri, P., Ascher, J.; Ceccherini, M.T.; Landi, L.,Pietramellara, G., Renella, G. 2003. Microbial diversity and soil functions. Eur.J. Soil Sci.,54, 655–670.

44. Nascimento, D. F., Leles, P. S. S., Oliveira Neto, S. N., Moreira, R. T. S., Alonso, J. M. 2012.Initial growth of six forest tree species in different spacing conditions. Cerne, 18, 1, 159–165.

45. Ohsowski, B. M., Klironomos, J. N., Dunfield, K. E., Hart, M. M. 2012. The potential of soil amendments for restoring severely disturbed grasslands. Applied Soil Ecology,60, 77–83.

46. Pagano, M.C. 2008. Composition of rhizobia associated with neotropical tree legume *Centrolobiumtomentosum* used in riparian restoration. Plant Soil and Environment, 54, 498–508.

47. Pagano, M.C., Scotti, M.R. 2008. Arbuscular and ectomycorrhizal colonization of two *Eucalyptus*speciesin semiarid Brazil. Mycoscience, 49, 379–384.

48. Pagano, M.C., Cabello, M.N., Bellote, A.F.,Sá, N.M., Scotti, M.R. 2008. Intercropping system of tropical leguminous species and *Eucalyptus camaldulensis*, inoculated with rhizobia and/or mycorrhizal fungi in semiarid Brazil.Agrofor. Syst., 74, 231–242.

49. Pagano, M.C., Scotti, M.R., Cabello, M.N. 2009. Effect of the inoculation and distribution of mycorrhizae in *Plathymenia reticulata*Benth under monoculture and mixed plantation in Brazil. New Forests, 38, 197–214.

50. Pagano, M.C., Cabello, M.N., Scotti, M.R. 2010a. Agroforestry In Dry Forest, Brazil: Mycorrhizal Fungi Potential. In: LR Kellymore, ed. Handbook on Agroforestry: Management Practices and Environmental Impact.Nova Science Publishers, New York. pp.367–388.

51. Pagano, M.C., Persiano, A.I.C., Cabello, M.N., Scotti, M.R. 2010b. Elements sequestered by arbuscular mycorrhizal spores in riverine soils: a preliminary assessment. Journal of Biophysics and Structural Biology, 2, 2, 16–21.

52. Pagano, M.C., Lugo, M.,Araújo, F., Ferrero, M., Menoyo, E. andSteinaker, D. (2012). Native species for restoration and conservation of biodiversity in South America. In: Marín L and Kovač D, editors, *Native Species: Identification, Conservation and Restoration*, Nova Science Publishers, New York, USA. pp. 1-55.

53. Pagano, M.C., Araújo, F.S.2011. Semiarid Vegetation In Brazil: Biodiversity, Impacts And Management.In: Degenovine KM., editor. Semi-Arid Environments: Agriculture, Water Supply and Vegetation. Nova Science Publishers, New York, pp. 99–114.

54. Pagano, M.C.,Utida, M.K., Gomes, E.A., Marriel, I.E., Cabello, M.N., Scotti, M.R. 2011. Plant-type dependent changes in arbuscular mycorrhizal communities as soil quality indicator in semi-arid Brazil. Ecological Indicators, 11, 2, 643–650.

55. Pagano, M.C.,ed.2012. Mycorrhiza: Occurrence in Natural and Restored Environments, USA. 327 p.

56. Pagano, M.C., Scotti, M.R., Cabello, M.N. 2012. Mycorrhizas, an important component in Semiarid Sites pp. 127–146. In: Mycorrhiza: Occurrence in Natural and Restored Environments, USA. Pagano M.C., ed.pp. 127–146.

57. Quesada,M., Sanchez-Azofeifa,G. A., Alvarez-Añorve,M.etal.2009. Succession and management of tropical dry forests in the Americas: Review and new perspectives. Forest Ecology and Management, 258, 1014–1024.

58. RahimForoughbakhch, P., Piñero,J. H., Vásquez, M.A.A., Avila,M. L. C. 2010. Use of multipurpose trees and shrubs in forestry and agroforestry systems in northeastern Mexico. In: LR Kellymore, ed. Handbook on Agroforestry: Management Practices and Environmental Impact. Nova Science Publishers, New York. pp.325–345.

59. Read, D.J. 2002. Towards ecological relevance – Progress and pitfalls in the path towards an understanding of mycorrhizal functions in nature. In: van der Heijden, M., Sanders, I.R. Mycorrhizal Ecology. Ecological Studies Analysis and Synthesis, Springer, Berlin, pp. 1–29.

60. Reis, A., Bechara, F. C.,Tres, D. R. 2010. Nucleation in tropical ecological restoration. Sci. Agric., 67, 2, 244–250.

61. Ren, H., Zhang, Q., Lu, H., Liu, H., Guo, Q., Wang, J., Jian, S., Bao, H. 2012. Wild Plant Species with Extremely Small Populations Require Conservation and Reintroduction in China. AMBIO. DOI 10.1007/s13280-012-0284-3.

62. Renker, C., Zobel, M., Opik, M., Allen, M.F., Allen, E.B., Vosátka, M.,Rydlová, J., Buscot, F. 2004. Structure, dynamics, and restorationof plant communities: do arbuscular mycorrhizae matter?In: Temperton, V.M., Hobbs, R., Nuttle, T., Halle, S., eds.Assemblyrules and restoration ecology. Island Press, Washington, DC,pp. 189–229.

63. Requena, N., Pérez-Solis, E., Azcón-Aguilar, C., Jeffries, P., Barea, J.M. 2001. Management of indigenous plantmicrobe symbiosis aids restoration of desertified ecosystems. Applied and Environmental Microbiology, 67, 495–498.

64. Rillig, M.C., Mummey, D.L., 2006. Mycorrhizas and soil structure. New Phytologist, 171, 41–53.

65. Rillig, M.C., Caldwell, B.A., Wösten, H.A.B., Sollins, P. 2007. Role of proteins in soilcarbon and nitrogen storage: controls on persistence. Biogeochemistry, 85,25–44.

66. Rodrigues AF et al. 2021 Systematic review of soil ecosystem services in tropical regions. R. Soc. Open Sci. 8: 201584. https://doi.org/10.1098/rsos.201584

67. Rodrigues,R. R.,Gandolfi,S.,Nave,A. G.,Aronson,J.,Barreto,T. E., Vidal,C. Y.,Brancalion,P.H.S. 2011.Large-scale ecological restoration of high-diversity tropical forests in SE Brazil.Forest Ecology and Management,261, 10, 1605–1613.

68. Ruiz-Jaen, M. C., Aide, T. M. 2005. Restoration Success: How Is It Being Measured? Restoration Ecology, 13, No. 3, 569–577.

69. Schäfer, T. Legal Protection Schemes for Free-Flowing Rivers in Europe: An Overview. Sustainability 2021, 13, 6423. https://doi.org/ 10.3390/su13116423

70. Scherr, S.J., McNeely, J.A. 2008. Biodiversity conservation and agricultural sustainability: towards a new paradigm of 'ecoagriculture' landscapes. Phil. Trans. R. Soc. B, 363, 477–94.

71. Smith, S.E., Read, D.J. Mycorrhizal Symbiosis. New York: Elsevier; 2008.

72. Soares, C. R. F. S., Carneiro, M. A. C. 2010.Micorrizas arbusculares na recuperação de áreas degradadas. In: Siqueira, J.O. et al., eds. Micorrizas: 30 anos de pesquisa no Brasil.Editora UFLA, Lavras, pp. 441–474.

73. Subramanian, K.S., Charest, C., Dwyer, L.M., Hamilton, R.I., 1995. Arbuscular mycorrhizas and water relations in maize under drought stress at tasseling. New Phytologist 129, 643–650.

74. Stürmer, S. L., Sgrott A.F., Braghirolli, F.L., Uhlmann, A., Pescador, R. 2012. Importance of arbuscular mycorrhizal fungi for recovery of riparian sites in Southern Brazil.In: Mycorrhiza: Occurrence in Natural and Restored Environments, USA. Pagano MC, ed., pp. 275–289.

75. Tabarelli, M., Peres, C. A., Melo, F.P.L. 2012.The 'few winners and many losers' paradigm revisited: Emerging prospects for tropical forest biodiversity. Biological Conservation, 155, 136–140.

76. Thompson, K., Bakker, J.P., Bekker, R.M. 1997. The soil seed banks of north west Europe: Methodology, density and longevity. Cambridge, Cambridge University Press.

77. van der Heijden, M., Sanders, I.R. 2002. Mycorrhizal Ecology. Ecological Studies Analysis and Synthesis, Springer, Berlin, 471p.

78. VeldmanJW., G E. Overbeck, D Negreiros, G Mahy, S Le Stradic, Fernandes G. W, Durigan G, E Buisson, 30, 2015,347, 6221 484Tyranny of trees in grassy biomes. Francis E. Putz, W J. Bond

79. Wang, B., Qiu, Y.L. 2006. Phylogenetic distribution and evolution of mycorrhizas in land plants. Mycorrhiza, 16,299–363.

80. Zangaro, W. 2012. Arbuscular mycorrhizasand their importance for tropical forest formation in Brazil. In: Mycorrhiza: Occurrence in Natural and Restored Environments, USA. Pagano M.C.,ed., pp. 49–73.