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Conference Report

Considering Soil Biota and Symbioses in Forest Management and Ecosystem Restoration

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Abstract: At the 16th Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region on 12–15 September 2022, the authors hosted a symposium on the topic of "Considering host-microbial interactions in ecosystem restoration". The goal of this symposium was to showcase studies that demonstrate how soil biota and symbioses can be used to promote forest restoration. Two key principles emerging from the symposium and research on this topic include the following: (1) diverse, native mixes of appropriate soil biota can meaningfully shift forests and plantings towards more successful and ecologically appropriate conditions; (2) context is important to consider in determining the appropriateness of plant and microbial pairings, including the similarity of source material and work sites across a variety of factors. To summarize the literature and discussion on this topic, we offer a graphical depiction of several of the factors to consider.

Keywords: forest management; ecological restoration; microbes; microbiome; microbial inoculation; mycorrhizae

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1. Introduction

Many ecosystems, especially forests, are rich with plant-microbial symbioses. This can include mycorrhizal fungi, which exchange soil resources for the products of photosynthesis with plant symbionts [1], as well as other kinds of fungi, bacteria, and fauna that help cycle nutrients, aerate soil, and more. Soil biota perform a variety of ecosystem services, including supporting forest resiliency to drought, pests, and other disturbances, providing nutrient cycling and soil formation, filtering contaminants, improving water infiltration into and retention in the soil, improving plant water use efficiency and plant access to water and other resources, and regulating plant community dynamics [2–5]. These services are crucial to healthy ecosystem functioning and the ability of forests to provide clean drinking water and adapt to climate change. There is growing evidence supporting efforts to harness these benefits for forest management and restoration, and research is revealing how protecting and restoring native soil biotic communities can be used to improve restoration, regeneration, productivity, and resiliency of many ecosystems, including forests [6–9].

To encourage collaboration among restoration practitioners, land managers, and research scientists, Northern Arizona University (NAU) hosts the Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region every other year (https://in.nau.edu/biennial-conference-of-science-management/; accessed 11 June 2023). For the 12–15 September 2022 gathering, the conference focused on the theme "Creating hope through action: advancing solutions to rapid environmental change". During this conference, the authors of this manuscript hosted a symposium entitled "Considering host-microbial interactions in ecosystem restoration", with the goal of providing examples of how soil microbes can be used in forest management and ecosystem restoration. Seven researchers from four research institutions highlighted key principles emerging from research on soil biota in ecosystems ranging from US Southwestern forests to grasslands. Below, we summarize and elaborate on the two key principles emerging from the symposium and literature on this topic.

2. Symposium Findings: Key Principles Emerging from Soil Biota and Forest Restoration Research

2.1. Diverse, Native Mixes of Appropriate Soil Biota Can Meaningfully Shift Forests and Plantings towards More Successful and Ecologically Appropriate Conditions

Protecting and restoring soil microbial communities using native topsoil and/or rhizosphere soil appropriate to the site has repeatedly emerged in the literature as an ecologically appropriate and highly successful technique that can outperform other restoration techniques such as hydrogels (e.g., [7,9–11]). At the symposium, Dr. Lisa Markovchick summarized the literature on this topic and presented a study evaluating whether the science is being implemented in management and restoration plans. Out of 130 management plans reviewed, only two mentioned mycorrhizal fungi or topsoil as a management and restoration consideration [3]. Results from the same review demonstrate the importance of this symposium and others like it, given the relative rarity of information available to land managers interested in leveraging soil biota for management goals.

Benefits of incorporating soil biota into land management can include improving seedling survival, strengthening the growth of target plant species, and reducing non-native reinvasion [7,9–11]. Dr. Hannah Farrell discussed the success of using topsoil and rhizosphere soil in her projects restoring degraded rangelands in the Southwestern US. Dr. Farrell and others have found that, in addition to contributing to the benefits of restoration plantings, this method is low-cost and low-technology [8,9,12,13]. Recent and upcoming studies by several of the presenters highlight the effectiveness of this method in a variety of contexts, including assisted migration [14,15].

In considering where to source soil inoculum, Dr. Matthew Bowker presented his work researching how soil from the home environment of plants can improve the success of restoration plantings. This has been shown to be effective with differing restoration goals in various ecosystems. One way of applying this method is to utilize microbes from the planting material source location [15–17]. Plants, microbes, and soil can be co-adapted at localized scales (e.g., [18–20]). As a result, mutualism may not yield the anticipated results when partners are not appropriately paired [21–23]. These co-adaptations may be one reason that using soil biota from a plant's home location can be a great option for introducing beneficial microbes to a restoration site [24]. It is unclear from the research how important planting and management site characteristics (such as soil salinity, other physical/chemical characteristics, and water source type/regularity) are compared to the plant and soil biota pairings, but some research indicates this is likely also important (e.g., [20]). Thus, the first key principle emerging from the symposium and research on this topic is that diverse, native mixes of appropriate soil biota can meaningfully shift forests and plantings towards more successful and ecologically appropriate conditions.

2.2. Context Is Important to Consider, including Site History, Machinery Use, Inter- and Intra-Specific Plant Diversity, and Source Material and Work Site Characteristics

While soil biota can benefit host plants, their effects vary greatly depending on the context in which the symbiosis is occurring [25–28]. Alexandra Schuessler, M.S., presented at the symposium about her work studying endophytic fungal effects on native Fremont cottonwood (*Populus fremontii* S. Wats.) and non-native tamarisk (*Tamarix* sp.) and how inoculation with distinct fungal species affects the two tree species differently. This principle is reflected in the literature, where plant responses to inoculation are often dependent upon species, intraspecific diversity, intraspecific adaptation, and other contexts [14,18,21,25,27–31]. Recent and upcoming research from symposium presenters and others repeatedly highlights this point: pairings among plant and fungal strains, source location characteristics, planting site characteristics, and even the timing of inoculation can all impact results. (e.g., [14,15,32–34]).

For example, mass-produced fungal inoculants typically have neutral to negative effects, often failing to produce healthier and more robust plants [32,33,35–37]. There are a variety of reasons why mass-produced inoculants are inappropriate for natural areas in terms of the goals and ethics of ecosystem restoration [38,39]. Mass-produced products can include fertilizer (which can have initial plant benefits but be counter-productive longer-term), preserved or dried microbes (creating a barrier for symbioses since plant roots often need direct contact with living, active fungi), and easily cultured, generalist species rather than the most appropriate specialist microbes (since many plant-dependent mycorrhizal fungi are difficult to culture). In addition to these more easily measured effects, inappropriately paired and mass-produced inoculants may prevent the most effective and appropriate native symbioses (e.g., [40]) and could even become invasive (e.g., [41]).

Additionally, while heavy machinery may be required for some management, restoration, and multiple-use activities, including the above recommendation, the heavier the machines and the greater the number of passes required, the greater the negative effects on both the soil and the soil biota become [42–45]. Dr. Kara Gibson presented at the symposium about her research regarding how machinery of varying weights negatively affects soil quality and the communities of microbes in those soils [46]. Rutting and soil compaction from machinery cause reduced soil porosity, nutrient recycling, drainage, and oxygen supply, and these harms can be both difficult to correct and long-lasting [42,47–49]. These effects translate to depressed tree and root growth and reduced microbial activity in affected soils, and this can affect the success of restoration [48,50,51].

However, in the right contexts, inoculation with microbes can significantly improve seedling survival, stimulate the growth of a target plant species, reduce non-native biomass and reinvasion, and promote restoration success and similarity to reference sites [8,9,12,13]. For example, Neuenkamp et al. found that mycorrhizal inoculation was associated with an increase in plant mass by an average effect size of 1.7 across 26 field studies and a 30% increase in species richness in restored plant communities, although the exact strength of the results was dependent on factors including species of plants and site history [7]. Discussions among researchers and forest managers after the symposium presentations reflected additional considerations in microbial inoculation, such as the site history and characteristics of both the plant material source sites and the sites being managed and/or restored. For example, sites that have had invasions by non-native vegetation are unlikely to be a quality source of soil microbiota, while sites that have been degraded or invaded by non-native vegetation are likely to benefit more from soil biotic restoration than ones that have not. These considerations are summarized in Figure 1. Thus, the second key principle emerging from this symposium and the literature is the fundamental importance of considering factors such as site history, machinery use, inter- and intra-specific plant diversity, source material history, and work site characteristics (Figure 1).

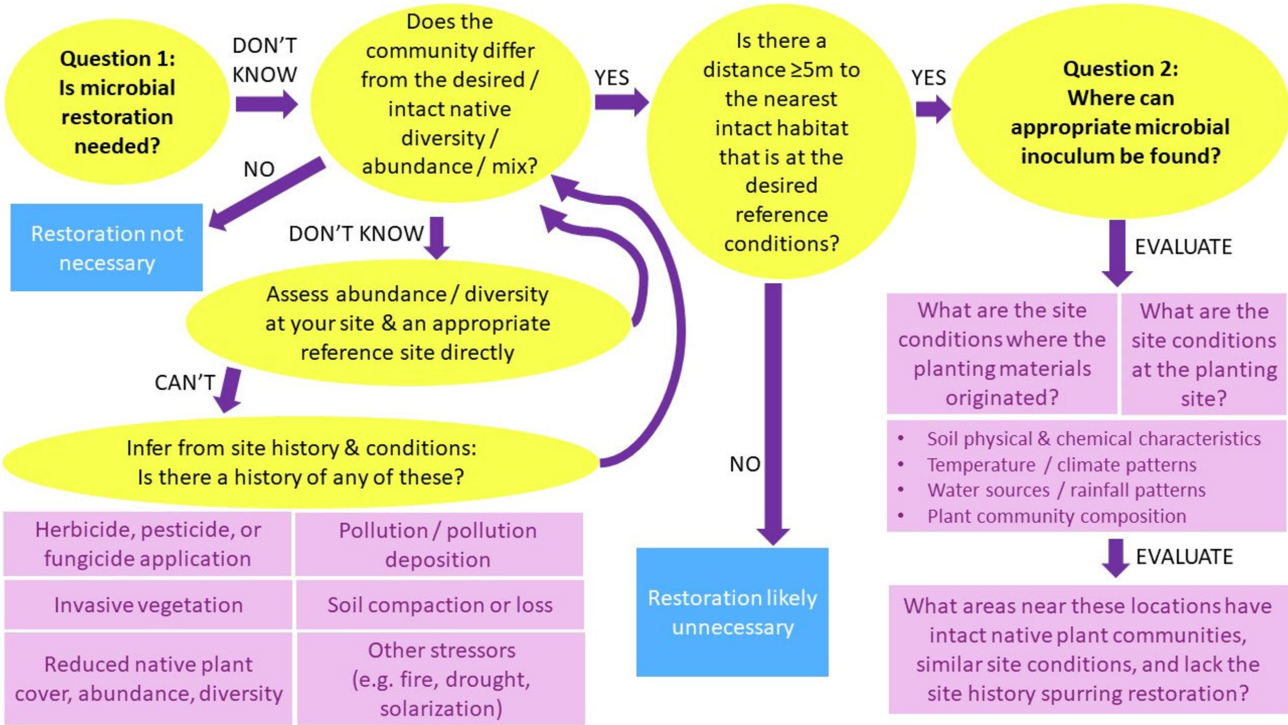

Figure 1. Factors to consider when evaluating the utility of microbial restoration in forest management [14,18–20,32–35,42–64]. Studies suggest that some soil biota, such as bacteria, may make swifter recoveries than mycorrhizal fungi and respond on different timelines and/or to different aspects of site history and characteristics (e.g., [53]). However, consistent principles regarding the importance of site history and characteristics and local co-adaptation suggest that these factors and considerations could be considered generally applicable.

3. Conclusions

The two key principles on host-microbial interactions emerging from this symposium and associated research can be distilled into the following: (1) diverse, native mixes of appropriate native soil biota can improve planting success and meaningfully shift forests towards more ecologically appropriate and successful conditions; (2) with microbial remediation efforts, context is fundamental to obtaining quality results, including site history and planting site similarity to planting material source sites. In cases where the site microbial communities are the same as those in surrounding intact areas or can be inferred to be intact based on site history (Figure 1), microbial restoration is not necessary. When a target site hosts a soil microbial community that is different from surrounding intact areas (or is likely different based on site history, as in Figure 1), the addition of soil biota may be a viable action to improve planting success at the target site. Proper sourcing of inocula is important for these actions (see Figure 1 for a summary of factors to consider), as are timing and handling (e.g., [34]). As long as context is heavily considered, soil microbial amendments to forest land are continuing to emerge as a potential method for supporting the diversity of native soil microbes, improving planting successes, and shifting plant communities towards goal compositions.

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References

1. Smith, S.E.; Read, D.J. The Roles of Mycorrhizas in Successional Processes and in Selected Biomes. In *Mycorrhizal Symbiosis*; Academic Press: Amsterdam, The Netherlands; Boston, MA, USA, 2008; p. 48, ISBN 978-0-12-370526-6.
2. Aislabie, J.; Deslippe, J.R. Soil Microbes and Their Contribution to Soil Services. In *Ecosystem Services in New Zealand–Conditions and Trends*; Manaaki Whenua Press: Lincoln, New Zealand, 2013.
3. Markovchick, L.M.; Carrasco-Denney, V.; Sharma, J.; Querejeta, J.I.; Gibson, K.S.; Swaty, R.; Uhey, D.A.; Belgara-Andrew, A.; Kovacs, Z.I.; Johnson, N.C.; et al. The Gap between Mycorrhizal Science and Application: Existence, Origins, and Relevance during the United Nation's Decade on Ecosystem Restoration. *Restor. Ecol.* **2023**, *31*, e13866. [CrossRef]
4. Philippot, L.; Spor, A.; Hénault, C.; Bru, D.; Bizouard, F.; Jones, C.M.; Sarr, A.; Maron, P.-A. Loss in Microbial Diversity Affects Nitrogen Cycling in Soil. *ISME J.* **2013**, *7*, 1609–1619. [CrossRef]
5. van der Heijden, M.G.A.; Bardgett, R.D.; van Straalen, N.M. The Unseen Majority: Soil Microbes as Drivers of Plant Diversity and Productivity in Terrestrial Ecosystems. *Ecol. Lett.* **2008**, *11*, 296–310. [CrossRef] [PubMed]
6. Graham, L.L.B.; Turjaman, M.; Page, S.E. *Shorea Balangeran* and *Dyera Polyphylla* (Syn. *Dyera Lowii*) as Tropical Peat Swamp Forest Restoration Transplant Species: Effects of Mycorrhizae and Level of Disturbance. *Wetl. Ecol. Manag.* **2013**, *21*, 307–321. [CrossRef]
7. Neuenkamp, L.; Prober, S.M.; Price, J.N.; Zobel, M.; Standish, R.J. Benefits of Mycorrhizal Inoculation to Ecological Restoration Depend on Plant Functional Type, Restoration Context and Time. *Fungal Ecol.* **2019**, *40*, 140–149. [CrossRef]
8. Wolfsdorf, G.; Abrahão, A.; D'Angioli, A.M.; Dechoum, M.D.S.; Meirelles, S.T.; Pecoral, L.F.L.; Rowland, L.; Verona, L.D.S.; Schmidt, I.B.; Sampaio, A.B.; et al. Inoculum Origin and Soil Legacy Can Shape Plant–Soil Feedback Outcomes for Tropical Grassland Restoration. *Restor. Ecol.* **2021**, *29*, e13455. [CrossRef]
9. Wubs, E.R.J.; van der Putten, W.H.; Bosch, M.; Bezemer, T.M. Soil Inoculation Steers Restoration of Terrestrial Ecosystems. *Nat. Plants* **2016**, *2*, 16107. [CrossRef]
10. Koziol, L.; Bever, J.D. AMF, Phylogeny, and Succession: Specificity of Response to Mycorrhizal Fungi Increases for Late-successional Plants. *Ecosphere* **2016**, *7*, e01555. [CrossRef]
11. Piñeiro, J.; Maestre, F.T.; Bartolomé, L.; Valdecantos, A. Ecotechnology as a Tool for Restoring Degraded Drylands: A Meta-Analysis of Field Experiments. *Ecol. Eng.* **2013**, *61*, 133–144. [CrossRef]
12. Duell, E.B.; O'Hare, A.; Wilson, G.W.T. Inoculation with Native Soil Improves Seedling Survival and Reduces Non-native Reinvasion in a Grassland Restoration. *Restor. Ecol.* **2023**, *31*, e13685. [CrossRef]
13. Farrell, H.L.; Léger, A.; Breed, M.F.; Gornish, E.S. Restoration, Soil Organisms, and Soil Processes: Emerging Approaches. *Restor. Ecol.* **2020**, *28*, S307–S310. [CrossRef]
14. Markovchick, L.M.; Schaefer, E.A.; Deringer, T.; Kovacs, Z.I.; Deckert, R.J.; Yazzie, J.; Dixit, A.; Propster, J.R.; Patterson, A.; Hultine, K.R.; et al. Post-Restoration Colonization Suggests Slow Regeneration, Plant Translocation Barriers, and Other Host/Symbiont Lessons during the United Nations' Decade on Ecosystem Restoration. *Restor. Ecol.* **2023**, e13940. [CrossRef]
15. Remke, M.J.; Hoang, T.; Kolb, T.; Gehring, C.; Johnson, N.C.; Bowker, M.A. Familiar soil conditions help *Pinus ponderosa* seedlings cope with warming and drying climate. *Restor. Ecol.* **2020**, *28*, S344–S354. [CrossRef]
16. Grman, E.; Allen, J.; Galloway, E.; McBride, J.; Bauer, J.T.; Price, P.A. Inoculation with Remnant Prairie Soils Increased the Growth of Three Native Prairie Legumes but Not Necessarily Their Associations with Beneficial Soil Microbes. *Restor. Ecol.* **2020**, *28*, S393–S399. [CrossRef]
17. Remke, M.J.; Johnson, N.C.; Bowker, M.A. Sympatric Soil Biota Mitigate a Warmer-drier Climate for *Bouteloua Gracilis*. *Glob. Chang. Biol.* **2022**, *28*, 6280–6292. [CrossRef]
18. Johnson, D.; Martin, F.; Cairney, J.W.G.; Anderson, I.C. The Importance of Individuals: Intraspecific Diversity of Mycorrhizal Plants and Fungi in Ecosystems. *New Phytol.* **2012**, *194*, 614–628. [CrossRef]
19. Johnson, N.C.; Tilman, D.; Wedin, D. Plant and Soil Controls on Mycorrhizal Fungal Communities. *Ecology* **1992**, *73*, 2034–2042. [CrossRef]
20. Johnson, N.C.; Wilson, G.W.T.; Bowker, M.A.; Wilson, J.A.; Miller, R.M. Resource Limitation Is a Driver of Local Adaptation in Mycorrhizal Symbioses. *Proc. Natl. Acad. Sci. USA* **2010**, *107*, 2093–2098. [CrossRef]
21. Gehring, C.A.; Sthultz, C.M.; Flores-Rentería, L.; Whipple, A.V.; Whitham, T.G. Tree Genetics Defines Fungal Partner Communities That May Confer Drought Tolerance. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 11169–11174. [CrossRef]

22. Hoeksema, J.D.; Hernandez, J.V.; Rogers, D.L.; Mendoza, L.L.; Thompson, J.N. Geographic Divergence in a Species-Rich Symbiosis: Interactions between Monterey Pines and Ectomycorrhizal Fungi. *Ecology* **2012**, *93*, 2274–2285. [CrossRef]
23. Revillini, D.; Gehring, C.A.; Johnson, N.C. The Role of Locally Adapted Mycorrhizas and Rhizobacteria in Plant–Soil Feedback Systems. *Funct. Ecol.* **2016**, *30*, 1086–1098. [CrossRef]
24. Connell, R.K.; Zeglin, L.H.; Blair, J.M. Plant Legacies and Soil Microbial Community Dynamics Control Soil Respiration. *Soil Biol. Biochem.* **2021**, *160*, 108350. [CrossRef]
25. Hoeksema, J.D.; Chaudhary, V.B.; Gehring, C.A.; Johnson, N.C.; Karst, J.; Koide, R.T.; Pringle, A.; Zabinski, C.; Bever, J.D.; Moore, J.C.; et al. A Meta-Analysis of Context-Dependency in Plant Response to Inoculation with Mycorrhizal Fungi. *Ecol. Lett.* **2010**, *13*, 394–407. [CrossRef]
26. Johnson, N.C.; Graham, J.H.; Smith, F.A. Functioning of Mycorrhizal Associations along the Mutualism-Parasitism Continuum. *New Phytol.* **1997**, *135*, 575–585. [CrossRef]
27. Petipas, R.H.; Wruck, A.C.; Geber, M.A. Microbe-mediated Local Adaptation to Limestone Barrens Is Context Dependent. *Ecology* **2020**, *101*, e03092. [CrossRef]
28. Smith, M.E.; Delean, S.; Cavagnaro, T.R.; Facelli, J.M. Evidence for Species-Specific Plant Responses to Soil Microbial Communities from Remnant and Degraded Land Provides Promise for Restoration. *Austral Ecol.* **2018**, *43*, 301–308. [CrossRef]
29. Patterson, A.; Flores-Rentería, L.; Whipple, A.; Whitham, T.; Gehring, C. Common Garden Experiments Disentangle Plant Genetic and Environmental Contributions to Ectomycorrhizal Fungal Community Structure. *New Phytol.* **2019**, *221*, 493–502. [CrossRef]
30. Blasini, D.E.; Koepke, D.F.; Bush, S.E.; Allan, G.J.; Gehring, C.A.; Whitham, T.G.; Day, T.A.; Hultine, K.R. Tradeoffs between Leaf Cooling and Hydraulic Safety in a Dominant Arid Land Riparian Tree Species. *Plant Cell Environ.* **2022**, *45*, 1664–1681. [CrossRef]
31. Blasini, D.E.; Koepke, D.F.; Grady, K.C.; Allan, G.J.; Gehring, C.A.; Whitham, T.G.; Cushman, S.A.; Hultine, K.R. Adaptive Trait Syndromes along Multiple Economic Spectra Define Cold and Warm Adapted Ecotypes in a Widely Distributed Foundation Tree Species. *J. Ecol.* **2021**, *109*, 1298–1318. [CrossRef]
32. Rúa, M.A.; Antoninka, A.; Antunes, P.M.; Chaudhary, V.B.; Gehring, C.; Lamit, L.J.; Piculell, B.J.; Bever, J.D.; Zabinski, C.; Meadow, J.F.; et al. Home-Field Advantage? Evidence of Local Adaptation among Plants, Soil, and Arbuscular Mycorrhizal Fungi through Meta-Analysis. *BMC Evol. Biol.* **2016**, *16*, 122. [CrossRef]
33. Maltz, M.R.; Treseder, K.K. Sources of Inocula Influence Mycorrhizal Colonization of Plants in Restoration Projects: A Meta-Analysis: Mycorrhizal Inoculation in Restoration. *Restor. Ecol.* **2015**, *23*, 625–634. [CrossRef]
34. Mortimer, P.E.; Archer, E.; Valentine, A.J. Mycorrhizal C Costs and Nutritional Benefits in Developing Grapevines. *Mycorrhiza* **2005**, *15*, 159–165. [CrossRef]
35. Corkidi, L.; Allen, E.B.; Merhaut, D.; Allen, M.F.; Downer, J.; Bohn, J.; Evans, M. Assessing the Infectivity of Commercial Mycorrhizal Inoculants in Plant Nursery Conditions. *J. Environ. Hortic.* **2004**, *22*, 149–154. [CrossRef]
36. Kaminsky, L.M.; Trexler, R.V.; Malik, R.J.; Hockett, K.L.; Bell, T.H. The Inherent Conflicts in Developing Soil Microbial Inoculants. *Trends Biotechnol.* **2019**, *37*, 140–151. [CrossRef]
37. Salomon, M.J.; Demarmels, R.; Watts-Williams, S.J.; McLaughlin, M.J.; Kafle, A.; Ketelsen, C.; Soupir, A.; Bücking, H.; Cavagnaro, T.R.; van der Heijden, M.G.A. Global Evaluation of Commercial Arbuscular Mycorrhizal Inoculants under Greenhouse and Field Conditions. *Appl. Soil Ecol.* **2022**, *169*, 104225. [CrossRef]
38. FAO; IUCN CEM; SER. *Principles for Ecosystem Restoration to Guide the United Nations Decade 2021–2030*; FAO: Rome, Italy, 2021. Available online: https://www.fao.org/3/cb6591en/cb6591en.pdf (accessed on 11 June 2023).
39. Gann, G.D.; McDonald, T.; Walder, B.; Aronson, J.; Nelson, C.R.; Jonson, J.; Hallett, J.G.; Eisenberg, C.; Guariguata, M.R.; Liu, J.; et al. International Principles and Standards for the Practice of Ecological Restoration. Second Edition. *Restor. Ecol.* **2019**, *27*, S1–S46. [CrossRef]
40. Janoušková, M.; Krak, K.; Vosátka, M.; Püschel, D.; Štorchová, H. Inoculation Effects on Root-Colonizing Arbuscular Mycorrhizal Fungal Communities Spread beyond Directly Inoculated Plants. *PLoS ONE* **2017**, *12*, e0181525. [CrossRef]
41. Hayward, J.; Horton, T.R.; Pauchard, A.; Nuñez, M.A. A Single Ectomycorrhizal Fungal Species Can Enable a *Pinus* Invasion. *Ecology* **2015**, *96*, 1438–1444. [CrossRef]
42. Hamza, M.A.; Anderson, W.K. Soil Compaction in Cropping Systems. *Soil Tillage Res.* **2005**, *82*, 121–145. [CrossRef]
43. Jordan, D.; Ponder, F.; Hubbard, V.C. Effects of Soil Compaction, Forest Leaf Litter and Nitrogen Fertilizer on Two Oak Species and Microbial Activity. *Appl. Soil Ecol.* **2003**, *23*, 33–41. [CrossRef]
44. Mohieddinne, H.; Brasseur, B.; Spicher, F.; Gallet-Moron, E.; Buridant, J.; Kobaissi, A.; Horen, H. Physical Recovery of Forest Soil after Compaction by Heavy Machines, Revealed by Penetration Resistance over Multiple Decades. *For. Ecol. Manag.* **2019**, *449*, 117472. [CrossRef]
45. Nawaz, M.F.; Bourrié, G.; Trolard, F. Soil Compaction Impact and Modelling. A Review. *Agron. Sustain. Dev.* **2013**, *33*, 291–309. [CrossRef]
46. Gibson, S.; Neher, D.A.; Jonhson, N.C.; Parmenter, R.R.; Antonika, J.A. Heavy Logging Machinery Impacts Soil Physical Properties More than Nematode Communities. *Forests* **2023**, *14*, 1205. [CrossRef]
47. Alakukku, L.; Weisskopf, P.; Chamen, W.C.T.; Tijink, F.G.J.; van der Linden, J.P.; Pires, S.; Sommer, C.; Spoor, G. Prevention Strategies for Field Traffic-Induced Subsoil Compaction: A Review. *Soil Tillage Res.* **2003**, *73*, 145–160. [CrossRef]
48. Cambi, M.; Certini, G.; Neri, F.; Marchi, E. The Impact of Heavy Traffic on Forest Soils: A Review. *For. Ecol. Manag.* **2015**, *338*, 124–138. [CrossRef]

49. Frey, B.; Kremer, J.; Rüdt, A.; Sciacca, S.; Matthies, D.; Lüscher, P. Compaction of Forest Soils with Heavy Logging Machinery Affects Soil Bacterial Community Structure. *Eur. J. Soil Biol.* **2009**, *45*, 312–320. [CrossRef]
50. Bassett, I.E.; Simcock, R.C.; Mitchell, N.D. Consequences of Soil Compaction for Seedling Establishment: Implications for Natural Regeneration and Restoration. *Austral Ecol.* **2005**, *30*, 827–833. [CrossRef]
51. von Wilpert, K.; Schäffer, J. Ecological Effects of Soil Compaction and Initial Recovery Dynamics: A Preliminary Study. *Eur. J. For. Res.* **2006**, *125*, 129–138. [CrossRef]
52. Meinhardt, K.A.; Gehring, C.A. Disrupting Mycorrhizal Mutualisms: A Potential Mechanism by Which Exotic Tamarisk Outcompetes Native Cottonwoods. *Ecol. Appl.* **2012**, *22*, 532–549. [CrossRef]
53. Zhong, Z.; Zhang, X.; Wang, X.; Fu, S.; Wu, S.; Lu, X.; Ren, C.; Han, X.; Yang, G. Soil Bacteria and Fungi Respond Differently to Plant Diversity and Plant Family Composition during the Secondary Succession of Abandoned Farmland on the Loess Plateau, China. *Plant Soil* **2020**, *448*, 183–200. [CrossRef]
54. Helander, M.; Saloniemi, I.; Omacini, M.; Druille, M.; Salminen, J.-P.; Saikkonen, K. Glyphosate Decreases Mycorrhizal Colonization and Affects Plant-Soil Feedback. *Sci. Total Environ.* **2018**, *642*, 285–291. [CrossRef] [PubMed]
55. Pánková, H.; Dostálek, T.; Vazačová, K.; Münzbergová, Z. Slow Recovery of Arbuscular Mycorrhizal Fungi and Plant Community after Fungicide Application: An Eight-Year Experiment. *J. Veg. Sci.* **2018**, *29*, 695–703. [CrossRef]
56. Hawkes, C.V.; Belnap, J.; D'Antonio, C.; Firestone, M.K. Arbuscular Mycorrhizal Assemblages in Native Plant Roots Change in the Presence of Invasive Exotic Grasses. *Plant Soil* **2006**, *281*, 369–380. [CrossRef]
57. Wilson, G.W.T.; Hickman, K.R.; Williamson, M.M. Invasive Warm-Season Grasses Reduce Mycorrhizal Root Colonization and Biomass Production of Native Prairie Grasses. *Mycorrhiza* **2012**, *22*, 327–336. [CrossRef]
58. Lilleskov, E.A.; Kuyper, T.W.; Bidartondo, M.I.; Hobbie, E.A. Atmospheric Nitrogen Deposition Impacts on the Structure and Function of Forest Mycorrhizal Communities: A Review. *Environ. Pollut.* **2019**, *246*, 148–162. [CrossRef]
59. Grünfeld, L.; Skias, G.; Rillig, M.C.; Veresoglou, S.D. Arbuscular Mycorrhizal Root Colonization Depends on the Spatial Distribution of the Host Plants. *Mycorrhiza* **2022**, *32*, 387–395. [CrossRef]
60. Hart, M.; Klironomos, J. Colonization of Roots by Arbuscular Mycorrhizal Fungi Using Different Sources of Inoculum. *Mycorrhiza* **2002**, *12*, 181–184. [CrossRef]
61. Hart, M.M.; Antunes, P.M.; Chaudhary, V.B.; Abbott, L.K. Fungal Inoculants in the Field: Is the Reward Greater than the Risk? *Funct. Ecol.* **2017**, *32*, 126–135. [CrossRef]
62. Jones, M.D.; Durall, D.M.; Cairney, J.W.G. Ectomycorrhizal Fungal Communities in Young Forest Stands Regenerating after Clearcut Logging. *New Phytol.* **2003**, *157*, 399–422. [CrossRef]
63. Peay, K.G.; Garbelotto, M.; Bruns, T.D. Evidence of Dispersal Limitation in Soil Microorganisms: Isolation Reduces Species Richness on Mycorrhizal Tree Islands. *Ecology* **2010**, *91*, 3631–3640. [CrossRef]
64. Parsons, W.F.J.; Miller, S.L.; Knight, D.H. Root-Gap Dynamics in a Lodgepole Pine Forest: Ectomycorrhizal and Nonmycorrhizal Fine Root Activity after Experimental Gap Formation. *Can. J. For. Res.* **1994**, *24*, 1531–1538. [CrossRef]