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Editorial: Plant-soil-microbe interactions and drivers in ecosystem development and ecological restoration

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Editorial on the Research Topic

Plant-soil-microbe interactions and drivers in ecosystem development and ecological restoration

Studies on the ecological restoration or rehabilitation of deeply disturbed and degraded ecosystems, and reintegration of fragmented, dysfunctional landscapes around the world report failures or unsatisfactory outcomes. These failures are increasingly attributed to inadequate consideration of substrate and its implications for plant and microbial establishment and survival (Mendes et al., 2019). Much greater knowledge of soil processes and interactions is needed if we are to develop techniques and technology that will help us come reasonably close to achieving global restoration aspirations (Cross et al. 2019; Aronson et al., 2020).

Better consideration of soil biota, and other critical edaphic factors, is clearly needed to ameliorate and revitalize substrate conditions and plant-soil interactions so as to sustainably restore and support indigenous microbial, invertebrate and vertebrate fauna, and vegetation communities, ecosystems and landscapes (Cross and Lambers, 2017; Cross et al., 2021a; Cross et al., 2021b). It has been proposed that, at least in some regions, soil characteristics and their changes through time likely represent among the strongest drivers, filters and leverages for species establishment, ecological succession and recovery, and overall effectiveness in ecological restoration and rehabilitation (ERR) projects (Bauer et al., 2015; Cross, 2021; Cross and Lambers, 2021).

The processes influencing pedogenesis and nutrient cycles in soils also impact the establishment and succession plant species and assemblages through time (Eger et al., 2011; Lambers et al., 2011; Laliberté et al., 2013). They are also dynamic and influenced in their turn by complex plant-soil, plant-microbe, and microbe-soil interactions (Lambers et al., 2008; van Schöll et al., 2008; Shanmugam and Kingery, 2018). Recent studies have identified substrate conditions limiting, or totally blocking ERR efforts. These include, but are not limited to, highly altered materials presenting ecologically hostile chemical environments (such as extreme pH), challenging hydrological and osmotic conditions, unsuitable macronutrient stoichiometry for ecologically specialized native vegetation, shortfalls of organic biomass, insufficient or disproportionate abundance of key functional soil microbial groups, or high concentrations of biologically toxic contaminants (Huang et al., 2012; Cross and Lambers, 2017; Cross et al., 2017; Busso and Pérez, 2018).

Recognition of these multiple, complex, and interwoven obstacles has led to significantly greater consideration of the role of substrate and edaphic factors in ERR (Nolan et al., 2021); this has reached the point of calls for projects to consider 'engineering' substrates that are suitable for desired biota following significant disturbance to substrates from activities such as mining (Huang et al., 2012; Kumaresan et al., 2017), or to artificially inoculate soils with commercial microbial blends (Farrell et al., 2020; Valliere et al., 2020; Contos et al., 2021), despite limited and inconsistent experimental evidence for the efficacy and risks associated with these techniques (Lance et al., 2019; Wong et al., 2022; Zhong et al., 2023).

Current understanding of the natural processes and mechanisms driving soil development and determining patterns of vegetation and microbial diversity and composition continues to hinder progress in ERR, as well as in related undertakings such as regenerative agriculture and urban regreening projects. But we must also support and learn from the pioneering sites, programs, networks, and breakthroughs taking place in the worldwide movement of ecological restoration and improved ecosystem management. In this collection of papers, we bring together articles on one of the critical focal and leverage points where we can intervene to improve ecosystem trajectories at terrestrial sites undergoing ERR: the intricate and complex ecosystems that are soils.

Our Research Topic solicited studies presenting empirical data pertaining to the interactive relationships connecting soil, soil microbes, invertebrates, and plants, aiming to enhance our understanding of soil and vegetation developmental processes in the context of ERR. As Tedesco et al. (2023) have recently summarized, and many other authors have provided evidence for, from long-term experimental restoration sites at landscape and smaller spatial scales (Jellinek et al., 2014; Budiharta et al., 2016; Hein et al., 2019; Hong et al., 2022): ecological restoration in today's world must go "beyond ecology" and become "a process for social-ecological transformation" (Tedesco et al., 2023). There is a risk otherwise that ERR activities will not achieve their full potential as an investment in human, social, cultural, and natural capital (Aronson et al., 2020). The global literature continues to add new and powerful evidence that soils and soil microbiota should be considered a very high priority for research and development, as key places to intervene along ecosystem recovery trajectories to advance and accelerate restoration processes (Nolan et al., 2021).

While none of the four articles in this Research Topic explicitly undertake or assess ecological restoration, each examines different mechanisms and processes relating to plant-soil-microbial interactions that have deep relevance to the theory and practice of ERR.

The first article by Beñares-de-Dios et al. provides a detailed examination of the literature pertaining to the role of soil and climate as determinants of floristic composition, focusing on tropical forests. The authors examine the relative importance of different environmental factors as drivers of plant species occurrence across different spatial scales and in different forest ecosystems. Beñares-de-Dios et al. contribute to growing understanding of the importance of soil and climatic factors as drivers of vegetation and microbial community patterns over large spatial scales. This builds upon the seminal work of Nottingham et al. (2018), and supports previous hypotheses around a strong importance of edaphic factors as determinants of species establishment and development at smaller scales in ERR (Cross, 2021; Cross et al., 2021a; Cross et al., 2021b).

Second, Fu et al. use high-throughput sequencing to evaluate the degree to which soil microbial diversity varies among different urban forest ecosystems as a function of soil and other environmental characteristics. The degree to which ecological degradation and, conversely, ERR, act as drivers of the diversity and composition of soil microbial communities has attracted significant international research interest in recent years (Hu et al., 2016; Li et al., 2016; Hamonts et al., 2017; Kumaresan et al., 2017; Deng et al., 2020). This interest has intensified with increasing accessibility and decreasing cost of sequencing technologies (Hart et al., 2020). Fu et al. report strong association between vegetation composition and microbial community, with considerable distinction in microbial diversity among different vegetation types, in line with previous studies highlighting soil microbes as powerful drivers of plant diversity (Van Der Heijden et al., 2008).

Thirdly, Jiang et al. examine the resource limitations influencing microbial communities in unique Karst tiankeng (limestone sinkhole) habitats, in the context of ecological degradation in these ecosystems, using soil ecoenzymatic stoichiometry. The contribution of microbial communities to biogeochemical cycling in ecological recovery activities, and the degree to which their natural contribution to ecological functioning is impaired by disturbance or degradation, is a topic of considerable interest in ERR (Hamman and Hawkes, 2013; Gagen et al., 2019; Moreira-Grez et al., 2019; Sun and Badgley, 2019). Jiang et al. notably report that level of degradation considerably impacts resource availability for microbial communities and contextualize their results around regional biodiversity conservation and restoration prioritization. The development of approaches prioritizing ERR activities to achieve maximum outcome is another hot topic in the international literature.

Lastly, He et al. present the results of an experimental pot study examining the potential utility of three perennial grasses in ameliorating soil contaminated with cadmium or petroleum hydrocarbons. Phytoremediation of contaminated soils in this manner (whether through the activity of plants, microbes, or both) is a growing international focus point (Pilon-Smits, 2005; Ali et al., 2013; Grison, 2015; Losfeld et al., 2015), particularly as a component of post-mining ERR where substrates, especially tailings, frequently contain high concentrations of heavy metals (Hur et al., 2011; Stojanović et al., 2012; Cross et al., 2017; Xie and van Zyl, 2020). He et al. assess the action of root exudates from the studied grasses in assisting the translocation of cadmium and petroleum hydrocarbons into above-ground biomass in different soils, and conclude that such root exudates likely represent a tool of significant utility in phytoremediation. Outcomes from their study contribute to a large and growing body of work improving our understanding of the complex mechanistic processes required to effectively ameliorate, and subsequently rehabilitate or restore, contaminated sites.

There is a clear and growing urgency for ecological restoration and rehabilitation, advanced phytoremediation, and other allied activities to be undertaken around the world. Ecological degradation is widespread and profound, eroding biodiversity and ecosystem functionality, not to mention landscape connectedness, and human health and wellbeing, at scales ranging from local all the way to the biospheric. Increasingly, scientists and practitioners are recognizing the crucial importance of soil and soil microbiota in ecosystem recovery in all ecological, and social-ecological systems. Stronger emphasis is being placed on these organisms when promoting and testing methods to support and maintain spontaneous recovery following degradation, and when undertaking active interventions for ERR in all contexts. As the four articles presented here illustrate, there are significant opportunities for examination of plant-soil-microbial interactions to improve the approaches, efficiencies, and outcomes of efforts to halt and reverse ecological damage to our global ecosystems.

Author contributions

AC and JA contributed equally to the development, writing, and editing of this article. Both authors contributed to the article and approved the submitted version.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Ali, H., Khan, E., and Sajad, M. A. (2013). Phytoremediation of heavy metals–concepts and applications. *Chemosphere* 91, 869–881. doi: 10.1016/j.chemosphere.2013.01.075

Aronson, J., Goodwin, N., Orlando, L., Eisenberg, C., and Cross, A. T. (2020). A world of possibilities: six restoration strategies to support the united nation's decade on ecosystem restoration. *Restor. Ecol.* 28, 730–736. doi: 10.1111/rec.13170

Bauer, J. T., Mack, K. M., and Bever, J. D. (2015). Plant-soil feedbacks as drivers of succession: evidence from remnant and restored tallgrass prairies. *Ecosphere* 6, 1–12. doi: 10.1890/ES14-00480.1

Budiharta, S., Meijaard, E., Wells, J. A., Abram, N. K., and Wilson, K. A. (2016). Enhancing feasibility: incorporating a socio-ecological systems framework into restoration planning. *Environ. Sci. Policy* 64, 83–92. doi: 10.1016/j.envsci.2016.06.014

Busso, C. A., and Pérez, D. R. (2018). Opportunities, limitations and gaps in the ecological restoration of drylands in Argentina. *Ann. Arid Zone* 57, 191–200.

Contos, P., Wood, J. L., Murphy, N. P., and Gibb, H. (2021). Rewilding with invertebrates and microbes to restore ecosystems: present trends and future directions. *Ecol. Evol.* 11, 7187–7200. doi: 10.1002/ece3.7597

Cross, A. T. (2021). Nutrient-acquisition strategy influences seed nutrient concentration and seed-to-seedling transition in ecological restoration in a regional dryland flora. *Plant Soil* 476, 1–16. doi: 10.1007/s11104-021-05198-z

Cross, A. T., Ivanov, D., Stevens, J. C., Sadler, R., Zhong, H., Lambers, H., et al. (2021b). Nitrogen limitation and calcifuge plant strategies constrain the establishment of native vegetation on magnetite mine tailings. *Plant Soil* 461, 181–201. doi: 10.1007/s11104-019-04021-0

Cross, A. T., and Lambers, H. (2017). Young calcareous soil chronosequences as a model for ecological restoration on alkaline mine tailings. *Sci. Total Environ.* 607, 168–175. doi: 10.1016/j.scitotenv.2017.07.005

Cross, A. T., and Lambers, H. (2021). Calcicole–calcifuge plant strategies limit restoration potential in a regional semi-arid flora. *Ecol. Evol.* 11, 6941–6961. doi: 10.1002/ece3.7544

Cross, A. T., Nevill, P. G., Dixon, K. W., and Aronson, J. (2019). Time for a paradigm shift toward a restorative culture. *Restor. Ecol.* 27, 924–928. doi: 10.1111/rec.12984

Cross, A. T., Stevens, J. C., and Dixon, K. W. (2017). One giant leap for mankind: can ecopoiesis avert mine tailings disasters? *Plant Soil* 421, 1–5. doi: 10.1007/s11104-017-3410-y

Cross, A. T., Stevens, J. C., Sadler, R., Moreira-Grez, B., Ivanov, D., Zhong, H., et al. (2021a). Compromised root development constrains the establishment potential of native plants in unamended alkaline post-mining substrates. *Plant Soil* 461, 163–179. doi: 10.1007/s11104-018-3876-2

Deng, J., Bai, X., Zhou, Y., Zhu, W., and Yin, Y. (2020). Variations of soil microbial communities accompanied by different vegetation restoration in an open-cut iron mining area. *Sci. Total Environ.* 704, 135243. doi: 10.1016/j.scitotenv.2019.135243

Eger, A., Almond, P. C., and Condron, L. M. (2011). Pedogenesis, soil mass balance, phosphorus dynamics and vegetation communities across a Holocene soil chronosequence in a super-humid climate, south westland, new Zealand. *Geoderma* 163, 185–196. doi: 10.1016/j.geoderma.2011.04.007

Farrell, H. L., Léger, A., Breed, M. F., and Gornish, E. S. (2020). Restoration, soil organisms, and soil processes: emerging approaches. *Restor. Ecol.* 28, S307–S310. doi: 10.1111/rec.13237

Gagen, E. J., Levett, A., Paz, A., Gastauer, M., Caldeira, C. F., da Silva Valadares, R. B., et al. (2019). Biogeochemical processes in canga ecosystems: armoring of iron ore against erosion and importance in iron duricrust restoration in Brazil. *Ore Geology Rev.* 107, 573–586. doi: 10.1016/j.oregeorev.2019.03.013

Grison, C. (2015). Combining phytoextraction and ecocatalysis: a novel concept for greener chemistry, an opportunity for remediation. *Environ. Sci. pollut. Res.* 22, 5589–5591. doi: 10.1007/s11356-014-3169-0

Hamman, S. T., and Hawkes, C. V. (2013). Biogeochemical and microbial legacies of non-native grasses can affect restoration success. *Restor. Ecol.* 21, 58–66. doi: 10.1111/j.1526-100X.2011.00856.x

Hamonts, K., Bissett, A., Macdonald, B. C., Barton, P. S., Manning, A. D., and Young, A. (2017). Effects of ecological restoration on soil microbial diversity in a temperate grassy woodland. *Appl. Soil Ecol.* 117, 117–128. doi: 10.1016/j.apsoil.2017.04.005

Hart, M., Cross, A., D'Agui, H., Dixon, K., van der Heyde, M., Moreira-Grez, B., et al. (2020). Examining assumptions of soil microbial ecology in the monitoring of ecological restoration. *Ecol. Solutions Evidence* 1, e12031. doi: 10.1002/2688-8319.12031

Hein, M. Y., Birtles, A., Willis, B. L., Gardiner, N., Beeden, R., and Marshall, N. A. (2019). Coral restoration: socio-ecological perspectives of benefits and limitations. *Biol. Conserv.* 229, 14–25. doi: 10.1016/j.biocon.2018.11.014

Hong, S. H., Lee, J. H., and An, M. Y. (2022). Socio-ecological restoration of cultural forests: the case of the gyeongju historic areas in south Korea. *Urban For. Urban Green.* 69, 127516. doi: 10.1016/j.ufug.2022.127516

Hu, Y. F., Peng, J. J., Yuan, S., Shu, X. Y., Jiang, S. L., Pu, Q., et al. (2016). Influence of ecological restoration on vegetation and soil microbiological properties in alpine-cold semi-humid desertified land. *Ecol. Eng.* 94, 88–94. doi: 10.1016/j.ecoleng.2016.05.061

Huang, L., Baumgartl, T., and Mulligan, D. (2012). Is rhizosphere remediation sufficient for sustainable revegetation of mine tailings? *Ann. Bot.* 110, 223–238. doi: 10.1093/aob/mcs115

Hur, M., Kim, Y., Song, H. R., Kim, J. M., Choi, Y. I., and Yi, H. (2011). Effect of genetically modified poplars on soil microbial communities during the phytoremediation of waste mine tailings. *Appl. Environ. Microbiol.* 77, 7611–7619. doi: 10.1128/AEM.06102-11

Jellinek, S., Rumpff, L., Driscoll, D. A., Parris, K. M., and Wintle, B. A. (2014). Modelling the benefits of habitat restoration in socio-ecological systems. *Biol. Conserv.* 169, 60–67. doi: 10.1016/j.biocon.2013.10.023

Kumaresan, D., Cross, A. T., Moreira-Grez, B., Kariman, K., Nevill, P., Stevens, J., et al. (2017). Microbial functional capacity is preserved within engineered soil formulations used in mine site restoration. *Sci. Rep.* 7, 564. doi: 10.1038/s41598-017-00650-6

Laliberté, E., Grace, J. B., Huston, M. A., Lambers, H., Teste, F. P., Turner, B. L., et al. (2013). How does pedogenesis drive plant diversity? *Trends Ecol. Evol.* 28, 331–340. doi: 10.1016/j.tree.2013.02.008

Lambers, H., Brundrett, M. C., Raven, J. A., and Hopper, S. D. (2011). Plant mineral nutrition in ancient landscapes: high plant species diversity on infertile soils is linked to functional diversity for nutritional strategies. *Plant Soil* 348, pp.7–pp27. doi: 10.1007/s11104-011-0977-6

Lambers, H., Chapin, F. S., and Pons, T. L. (2008). *Plant physiological ecology* Vol. 2 (New York: Springer), 11–99.

Lance, A. C., Burke, D. J., Hausman, C. E., and Burns, J. H. (2019). Microbial inoculation influences arbuscular mycorrhizal fungi community structure and nutrient dynamics in temperate tree restoration. *Restor. Ecol.* 27 (5), pp.1084–1093. doi: 10.1111/rec.12962

Li, Y., Jia, Z., Sun, Q., Zhan, J., Yang, Y., and Wang, D. (2016). Ecological restoration alters microbial communities in mine tailings profiles. *Sci. Rep.* 6 (1), 25193. doi: 10.1038/srep25193

Losfeld, G., L'Huillier, L., Fogliani, B., Jaffré, T., and Grison, C. (2015). Mining in new Caledonia: environmental stakes and restoration opportunities. *Environ. Sci. pollut. Res.* 22, 5592–5607. doi: 10.1007/s11356-014-3358-x

Mendes, M. S., Latawiec, A. E., Sansevero, J. B., Crouzeilles, R., Moraes, L. F., Castro, A., et al. (2019). Look down–there is a gap–the need to include soil data in Atlantic forest restoration. *Restor. Ecol.* 27, 361–370. doi: 10.1111/rec.12875

Moreira-Grez, B., Tam, K., Cross, A. T., Yong, J. W., Kumaresan, D., Nevill, P., et al. (2019). The bacterial microbiome associated with arid biocrusts and the biogeochemical influence of biocrusts upon the underlying soil. *Front. Microbiol.* 10, 2143. doi: 10.3389/fmicb.2019.02143

Nolan, M., Stanton, K. J., Evans, K., Pym, L., Kaufman, B., and Duley, E. (2021). From the ground up: prioritizing soil at the forefront of ecological restoration. *Restor. Ecol.* 29, 13453. doi: 10.1111/rec.13453

Nottingham, A. T., Fierer, N., Turner, B. L., Whitaker, J., Ostle, N. J., McNamara, N. P., et al. (2018). Microbes follow Humboldt: temperature drives plant and soil microbial diversity patterns from the Amazon to the Andes. *Ecology* 99, 2455–2466. doi: 10.1002/ecy.2482

Pilon-Smits, E. (2005). Phytoremediation. *Annu. Rev. Plant Biol.* 56, 15–39. doi: 10.1146/annurev.arplant.56.032604.144214

Shanmugam, S. G., and Kingery, W. L. (2018). Changes in soil microbial community structure in relation to plant succession and soil properties during 4000 years of pedogenesis. *Eur. J. Soil Biol.* 88, 80–88. doi: 10.1016/j.ejsobi.2018.07.003

Stojanović, M. D., Mihajlović, M. L., Milojković, J. V., Lopičić, Z. R., Adamović, M., and Stanković, S. (2012). Efficient phytoremediation of uranium mine tailings by tobacco. *Environ. Chem. Lett.* 10, 377–381. doi: 10.1007/s10311-012-0362-6

Sun, S., and Badgley, B. D. (2019). Changes in microbial functional genes within the soil metagenome during forest ecosystem restoration. *Soil Biol. Biochem.* 135, 163–172. doi: 10.1016/j.soilbio.2019.05.004

Tedesco, A. M., López-Cubillos, S., Chazdon, R., Rhodes, J. R., Archibald, C. L., Pérez-Hämmerle, K. V., et al. (2023). Beyond ecology: ecosystem restoration as a process for social-ecological transformation. *Trends Ecol. Evol.* doi: 10.1016/j.tree.2023.02.007

Valliere, J. M., Wong, W. S., Nevill, P. G., Zhong, H., and Dixon, K. W. (2020). Preparing for the worst: utilizing stress-tolerant soil microbial communities to aid ecological restoration in the anthropocene. *Ecol. Solutions Evidence* 1, e12027. doi: 10.1002/2688-8319.12027

Van Der Heijden, M. G., Bardgett, R. D., and Van Straalen, N. M. (2008). The unseen majority: soil microbes as drivers of plant diversity and productivity in terrestrial ecosystems. *Ecol. Lett.* 11, 296–310. doi: 10.1111/j.1461-0248.2007.01139.x

van Schöll, L., Kuyper, T. W., Smits, M. M., Landeweert, R., Hoffland, E., and Breemen, N. V. (2008). Rock-eating mycorrhizas: their role in plant nutrition and biogeochemical cycles. *Plant Soil* 303, 35–47. doi: 10.1007/s11104-007-9513-0

Wong, W. S., Morald, T. K., Whiteley, A. S., Nevill, P. G., Trengove, R. D., Yong, J. W., et al. (2022). Microbial inoculation to improve plant performance in mine-waste substrates: a test using pigeon pea (*Cajanus cajan*). *Land Degradation Dev.* 33, 497–511. doi: 10.1002/ldr.4165

Xie, L., and van Zyl, D. (2020). Distinguishing reclamation, revegetation and phytoremediation, and the importance of geochemical processes in the reclamation of sulfidic mine tailings: a review. *Chemosphere* 252, 126446. doi: 10.1016/j.chemosphere.2020.126446

Zhong, H., San Wong, W., Zhou, J., Cross, A. T., and Lambers, H. (2023). Restoration on magnetite mine waste substrates using Western Australian native plants only marginally benefited from a commercial inoculant. *Ecol. Eng.* 192, p.106991. doi: 10.1016/j.ecoleng.2023.106991