# Moving restoration ecology forward with combinatorial approaches

Matthias Rillig[1], Anika Lehmann[2], Rebecca Rongstock[1], Huiying Li[1], and Jim Harris[3]

[1]Free University of Berlin
[2]Freie Universität Berlin
[3]Cranfield University

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**Abstract**

Our current planetary crisis moves the need for effective ecosystem restoration centerstage and compels us to explore unusual options. We here propose exploring combinatorial approaches to restoration practices: management practices are drawn at random and combined from a locally relevant pool of possible management interventions, thus creating an experimental gradient in the number of interventions. This will move the current degree of interventions to higher dimensionality, opening new opportunities for unlocking unknown synergistic effects. In this concept, regional restoration hubs play an important role as guardians of locally relevant information and sites of experimental exploration. Data collected from such studies could feed into a global database, which could be used to learn about general principles of combined restoration practices, helping to refine future experiments. Such combinatorial approaches to exploring restoration intervention options may be our best hope yet to achieve decisive progress in ecological restoration at the timescale needed to mitigate and reverse the most severe losses.

*Viewpoint*

**Moving restoration ecology forward with combinatorial approaches**

Matthias C. Rillig [1,2*], Anika Lehmann[1,2], Rebecca Rongstock [1,2], Huiying Li [1,2], James Harris [3]

*1 Freie Universität Berlin, Institute of Biology, 14195 Berlin, Germany*

*2 Berlin-Brandenburg Institute of Advanced Biodiversity Research, 14195 Berlin, Germany*

*3 Cranfield Environment Centre, School of Water Energy and Environment, Cranfield University, Cranfield, Bedfordshire MK43 0AL, UK*

All author emails:

rillig@zedat.fu-berlin.de, lehmann.anika@googlemail.com, r.rongstock@fu-berlin.de, huiying.li@rwth-aachen.de, j.a.harris@cranfield.ac.uk

*Corresponding author. M. Rillig, Freie Universität Berlin, Institute of Biology, Altensteinstr. 6, 14195 Berlin, Germany; +49 30 838 53165; rillig@zedat.fu-berlin.de

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**Abstract**

Our current planetary crisis moves the need for effective ecosystem restoration centerstage and compels us to explore unusual options. We here propose exploring combinatorial approaches to restoration practices: management practices are drawn at random and combined from a locally relevant pool of possible management interventions, thus creating an experimental gradient in the number of interventions. This will move the current degree of interventions to higher dimensionality, opening new opportunities for unlocking unknown synergistic effects. In this concept, regional restoration hubs play an important role as guardians of locally relevant information and sites of experimental exploration. Data collected from such studies could feed into a global database, which could be used to learn about general principles of combined restoration practices, helping to refine future experiments. Such combinatorial approaches to exploring restoration intervention options may be our best hope yet to achieve decisive progress in ecological restoration at the timescale needed to mitigate and reverse the most severe losses.

Our planetary system is in crisis - at least 1.2 million plant and animal species are estimated to be under threat of extinction (IPBES 2019), many of them before 2100, and global warming is likely to reach 1.5°C between 2030 and 2052 if it continues to increase at the current rate (IPCC 2022) (IPCC, 2018). As we are exceeding an increasing number of planetary boundaries (Steffen *et al.* 2015), the need for effective ecosystem restoration moves centerstage. The currently unfolding United Nations Decade on Ecosystem Restoration therefore marks an important occasion to move the conversation on restoration approaches forward.

Restoration is an important tool for reversing biodiversity loss, but also for increasing carbon storage, and for countering the effects of global change, and ideally all three. Restoration has a rich and increasing toolkit of individual measures that generally serve to accelerate the movement of the system to later successional stages (Harris 2009). These consist of abiotic interventions (addressing substrate adversity, inappropriate nutrient content, or poor structure), and biotic interventions (addition of desired species, soil biota transplants, or removal of invasive species). While having made huge strides, in practice many restoration efforts do not fully succeed (Duguma *et al.* 2020), and there is even chronic under-reporting of failure (Hobbs 2009).

Add to this that ecosystems face ever-increasing human-caused challenges (Bowler *et al.* 2020), with the list of factors of global change steadily going up. We now know that an increasing number of human-caused factors impinging on an ecological system simultaneously can trigger responses not seen when just a few factors are active, including loss in functions and biodiversity (Rillig *et al.* 2019; Speißer *et al.* 2022; Zandalinas *et al.* 2021). The problems facing ecosystems are multifactorial and are becoming increasingly so, and research has not even fully grappled with this fact, as an analysis of the number of experimental factors included in global change experiments shows: over 98% of published studies use only one or two such factors (Rillig *et al.* 2019).

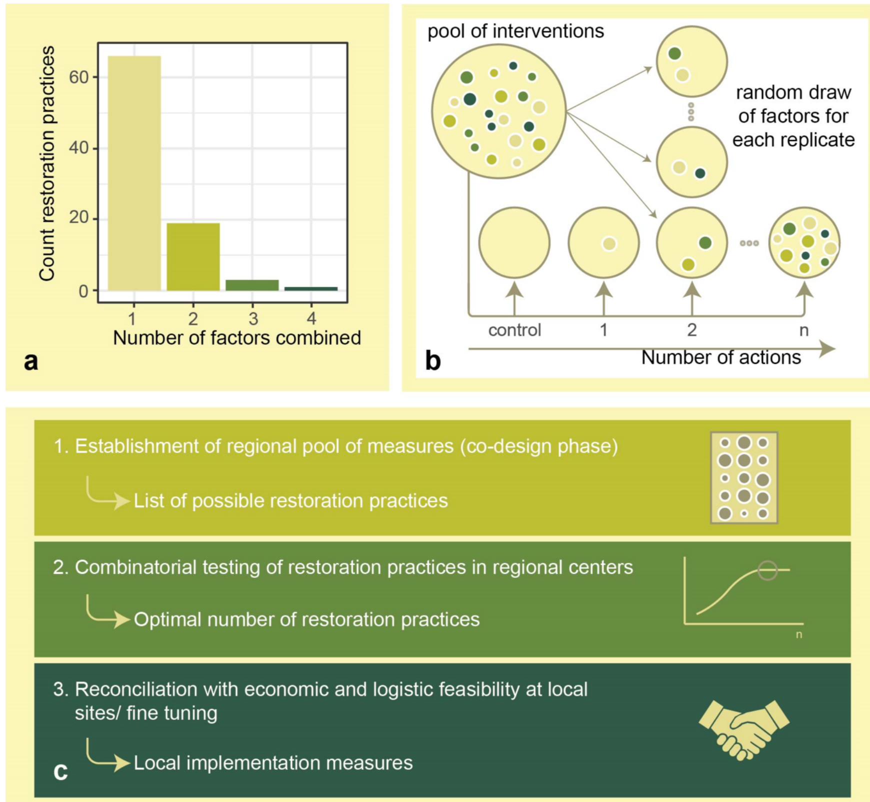


***Fig. 1*** *(a) Restoration projects currently only take advantage of a small number of practices or management interventions, as shown by these data on the number of restoration practices per study, collected from a meta-analysis* (Benayas *et al.* 2009) *of restoration studies. (b) Proposed combinatorial approach to experiments with larger numbers of factors. A gradient in the number of restoration actions is achieved by random sampling from a pool of possible actions. (c ) The proposed three-step workflow from establishing a regional pool of measures, to the combinatorial experimental testing approach (see panel b) to the reconciliation with local realities, leading to local implementation.*

Similarly, in the vast majority of cases restoration projects are either focused on a single issue (e.g., missing trees or herbivores or presence of a soil contaminant) or a general approach consisting of a small set of standard interventions (Benayas *et al.* 2009), rarely looking at anything other than vegetation establishment, let alone whole ecosystem assessment and intervention (Cross *et al.* 2019). In fact, the number of particular combinations of these individual measures that has been experimentally tested is relatively small (Fig. 1a) and pales in comparison to the vast space formed by all possible combinations that could be applied, let alone the combination of pressures at a variety of scales (Walker *et al.* 2014), and encompassing approaches which have been largely ignored, such as increasing complexity, both trophically and structurally (Bullock *et al.* 2022). Furthermore the effect of intensity of intervention is difficult to assess for more than a single factor (Li *et al.*2022). In other words, there is a clear gap between the parameter space of restoration measures that is possible and the space that has been explored so far. This is a situation similar to agricultural measurement, where only a small percentage of management combinations have ever been experimentally tested (Rillig & Lehmann 2019).

Factorial experiments, where factors (here management actions) are combined with each other into treatments, are fundamentally unsuited for dealing with a very large number of factors because of the combinatorial explosion problem (Katzir *et al.* 2019): the number of combinations increases rapidly with the number of factors to consider. This partly explains why so few management practices have been tested in combination

(Fig. 1a). A combinatorial approach, inspired from earlier work on the role of the number of species in biodiversity-ecosystem functioning experiments, namely randomly picking management actions from a pool of site-filtered options, is a possible solution, since this uses far fewer experimental units.

How could this work in practice (Fig. 1b,c)? Ecological restoration researchers and practitioners first need to agree on a pool of management interventions that are generally viable for a site and problem at hand, a list that in many cases will already be available. The research phase would then entail a pilot study in which treatments are picked from this pool of possible actions at random (Rillig *et al.* 2019), and combined into a gradient of the number of actions, ideally from 1 to n, with n being the pool size of management actions. Each replicate within this gradient of 'number of management interventions' will have a different, randomly chosen combination of actions. From this, an optimal number of interventions, both biotic and abiotic (sensu (Hobbs & Harris 2001)) could be identified to deliver accelerated gains in biodiversity and ecosystem functions. We postulate the existence of such an optimal number of interventions, since beyond a certain point there likely will be no further worthwhile gains; and it is very unlikely that a very low number of actions would already deliver successful restoration, as past experience shows (Duguma *et al.*2020). This result will then need to be reconciled with logistical and economic feasibility before being more widely applied at individual sites. Furthermore, combinations of treatment could be tuned to particular goals (e.g. wildlife, carbon sequestration), and challenges within particular sites, regions and biomes. We envision regional hubs that serve as centers for this kind of combinatorial testing, similar to agricultural experiment stations, which would also be able to test and secure cultural engagement. These regional hubs would hold and continually refine knowledge about locally relevant site conditions that provide important context for any restoration endeavor, such as soil properties or climate, and such hubs would also keep indigenous and local knowledge.

Funding, logistics, and availability of land or buy-in of land-owners will likely be major obstacles for this idea. Land-owners will be disinclined to offer their land for experimentation, and would need to be offered monetary compensation. We also envision that this will not work for all situations, but rather where relatively small plots could be informative for restoration outcomes (e.g. grasslands rather than forests). Clearly, situations in which large plot sizes are required would be unlikely to be suitable for this approach.

With data accumulating and being curated at regional hubs or a central, global data platform, it will be possible to learn important lessons about the nature of the management factor combinations that are successful, offering opportunities to constrain random draws of any future studies. For example, will it be more advantageous to have several rather similar practices (targeting particular features of the restored ecosystem, for example the soil); or would it be better to have a spread of interventions targeting as many different ecosystem components as possible? For this purpose a trait-based classification of management interventions, as already proposed for environmental factors (Rillig *et al.* 2021), may prove useful. In addition to such a 'bird's eye' view on factor combinations, research lines should also mechanistically explore successful factor combinations to understand better why they produce synergistic effects. In some cases this synergism is already clear, such as in co-application of biochar and fertilizer (Bai *et al.* 2022), but many such synergisms still await discovery.

Restoration practitioners routinely include multiple interventions in their efforts to reinvigorate ecosystems. While they do not do this in the context of formal experimentation, this may be a source of information that could be leveraged for the approach we propose here. In addition to the experimental focus we propose here, observational data could also be brought to bear on this question: analysis of data from practitioners on combinations they have used (especially their number) might also carry a signature that supports the premise of using combinatorial approaches.

We believe that testing this increased number of potential management interventions will unlock unprecedented advantages and restoration successes that are currently difficult to achieve or predict from single or few-factor management approaches. Such combinatorial approaches to exploring restoration intervention options, especially when conducted in the context of international restoration research networks, may be our best hope yet to achieve decisive progress in ecological restoration at the timescale needed to mitigate and reverse the most severe losses (Weise *et al.* 2020).

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