Step back from the forest and step up to the Bonn Challenge: How a broad ecological perspective can promote successful landscape restoration

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INVITED STRATEGIC ARTICLE

Step back from the forest and step up to the Bonn Challenge: how a broad ecological perspective can promote successful landscape restoration

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We currently face both an extinction and a biome crisis embedded in a changing climate. Many biodiverse ecosystems are being lost at far higher rates than they are being protected or ecologically restored. At the same time, natural climate solutions offer opportunities to restore biodiversity while mitigating climate change. The Bonn Challenge is a U.N. programme to restore biodiversity and mitigate climate change through restoration of the world's degraded landscapes. It provides an unprecedented chance for ecological restoration to become a linchpin tool for addressing many environmental issues. Unfortunately, the *Forest and Landscape Restoration* programme that underpins the Bonn Challenge, as its name suggests, remains focused on trees and forests, despite rising evidence that many non-forest ecosystems also offer strong restoration potential for biodiversity and climate mitigation. We see a need for restoration to *step back* to be more inclusive of different ecosystem types and to *step up* to provide integrated scientific knowledge to inform large-scale restoration. Stepping back and up will require assessments of *where* to restore *what* species, with recognition that in many landscapes multiple habitat types should be restored. In the process, trade-offs in the delivery of different ecosystem services (e.g. carbon, biodiversity, water, albedo, livestock forage) should be clearly addressed. We recommend that biodiversity safeguards be included in policy *and* implemented in practice, to avoid undermining the biophysical relationships that provide ecosystem resilience to climate change. For ecological restoration to contribute to international policy goals will require integrated large-scale science that works across biome boundaries.

Key words: Anthropocene, biodiversity, carbon storage, ecological restoration, ecosystem service, multifunctional landscapes, restoration ecology, sustainability, stakeholders

Implications for Practice

- In a global biome crisis, we need to take care that all ecosystems and habitats receive attention for restoration: Bonn Challenge in action should be called *Landscape Restoration*, not *Forest Landscape Restoration*.
- Policymakers should recognize knowledge gaps and strive to fill them using large-scale science programmes that involve both natural and social scientific approaches.
- Restoration should, whenever possible, focus on maximizing biodiversity to promote ecosystem resilience, and thus long-term adaptive capacity to provide ecosystem services in the face of climate change.
- Fulfilling international commitments for ecological restoration, in combination with halting the degradation of natural habitat, will provide a major step towards resolving pressing environmental problems.

Introduction

The Bonn Challenge is a policy-driven platform that has catapulted the field of ecological restoration onto the global science-policy stage. The framers of the Bonn Challenge envisioned restoration as a climate mitigation tool, whereby

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biodiversity is restored to degraded landscapes, carbon (C) is stored, and livelihoods of local populations can be improved. Launched by the government of Germany and International Union for Conservation of Nature in 2011, the Bonn Challenge aims to restore 150 million hectares of the world's deforested and degraded land by 2020 and 350 million hectares by 2030; it was later endorsed and extended by the New York Declaration on Forests at the 2014 UN Climate Summit (http://www.bonnchallenge.org/content/challenge). *The Forest (and) Landscape Restoration (FLR)* approach forms the basis of the Bonn Challenge, aiming to restore ecological integrity while also improving human well-being through multifunctional (forest) landscapes.

In the recently declared *UN Decade of Ecosystem Restoration* (2021–2030), these ambitious aims form an unprecedented opportunity for both the practice of ecological restoration as well as the scientific field of restoration ecology. Ecological restoration is still young as a discipline, and platforms such as the Bonn Challenge provide major opportunities for scaling up the benefits of ecological restoration to the global scale, linking it to existing programmes that combat ecosystem degradation such as REDD+. Within programmes of this magnitude, including many projects at the local and regional scale, restoration has the potential to become a linchpin tool for restoring biodiversity and maintaining human livelihoods through multifunctional landscapes. Importantly, the goals of the Bonn Challenge increasingly enter into public debates, as highlighted by a recent article in *The Guardian*. Carrington (2017) describes seven *global megatrends* that provide hope in the quest to curb climate change. Megatrend number seven is entitled "Forests—seeing the wood" and describes the potential to store carbon via massive planting of trees and reforestation and afforestation. Examples like this place restoration in the limelight, but also exemplify a common bias towards specific biome and habitat types in the debate: forests are often assumed to be the best ecosystems for mitigation of climate change, even though other ecosystem types also could be excellent candidates for natural climate solutions (Griscom et al. 2017).

Indeed, the very recent emergence of the inclusive term "natural climate solutions" (Griscom et al. 2017) invites us to consider the restoration of a whole range of different habitat types as a means to address "the global environmental challenges humanity, and biodiversity, faces." It is well-known that the wording and focus people use reflects quite directly on engagement, policy decisions, and also focus of scientific research (Jacobs et al. 2005; McNie 2007; Seddon et al. 2019). Indeed, Seddon et al. (2019), who advocate conservation solutions based on sound biodiversity science, express their concern on aspects of the (forest-focused) narrative that is currently reaching policymakers: they "call on scientists studying biodiversity and ecosystem functions and services to fully engage with and inform the process by which high-level pledges are translated into on-the-ground actions."

The unprecedented opportunity for scaling up ecological restoration thus clearly also presents an array of challenges and potential pitfalls. Such obstacles will be important to address swiftly as the Bonn Challenge, with its ambitious aims, unfolds. We argue that restoration ecologists need to *step back* to assess the underlying assumptions and unconscious biases within FLR policy. We also need to *step up* to develop and integrate the science to bolster the Bonn Challenge. In addition to broadening the biome narrative—currently focused mainly on forest and tree planting—we also need to take into consideration whether we are really doing ecological restoration, or whether we misuse the term for activities that are, in fact, reclamation or rehabilitation (Fig. 1; see also Suding et al. 2015), or, needless to say much worse, conversion by afforestation of natural biodiverse ecosystems (Veldman et al. 2015*a*, 2015*b*). Given these challenges, we have a need, but also a clear opportunity, for large-scale integrated research to improve the scientific basis for restoration. Only through restoration in all kinds of habitats, while aiming for high biodiversity wherever possible, can we actually gain the most out of such a huge potential for mitigating climate change, and provide strong multifunctionality (sensu Suding et al. 2015).

Explicit consideration of the overall framing of the Bonn Challenge and engaging in an open discussion of its implications for restoration practice on the ground is particularly important due to the predominance of tree-planting and forest restoration in FLR (Chazdon & Laestadius 2016; Veldman et al. 2017). We see a continued focus on trees as a blind spot to the true potential for restoring biodiversity, mitigating climate change, and improving local livelihoods in a whole range of different habitats and biomes (Seddon et al. 2019). Originally the programme was called *Forest Landscape Restoration* with a focus on reforestation and afforestation of degraded land, but then, partly in response to concern of scientists about the potential negative effect of afforesting biodiverse natural grasslands or savannas (Veldman et al. 2015*a*), was renamed *Forest and Landscape Restoration*. Subsequently, Chazdon et al. (2017) proposed four principles upon which FLR should be based, including avoiding afforestation of grassy (tropical) biomes, promoting landscape heterogeneity and biodiversity, distinguishing recent from residual carbon stocks, and diversifying local livelihoods.

Despite these modifications, the current programmes behind the Bonn Challenge, FLR, seem, by definition, to treat the restoration of other habitats as secondary (e.g. Chazdon & Laestadius 2016; Chazdon et al. 2017; Mansourian et al. 2017). While forests will certainly remain important to achieve the aims of the Bonn Challenge in many regions around the world, there is enormous potential to be inclusive and implement restoration in a wide range of biomes and thus mitigate climate change and reverse biodiversity loss in the best possible way for each particular geographical region and landscape.

Although coastal and marine habitats are not in the focus of this paper, coastal vegetation, including mangroves, seagrass communities, salt marshes and macroalgae harbour vast amouonts of carbon in marine seditments and provide resilience against extreme weather events by dissipating wave action and rising sea level (McLeod et al. 2011; Duarte et al. 2013). A continued, narrow focus on forests will compromise global conservation targets that call for consideration of all ecosystem types (Griscom et al. 2017), as well as provisioning of ecosystem services provide by all kinds of natural ecosystems, not only of

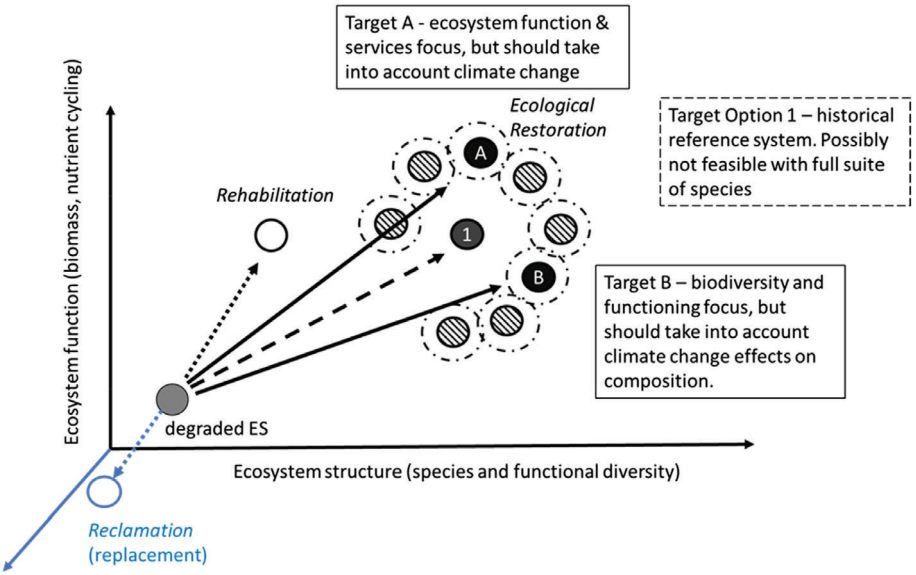

Figure 1. Comparison of outcomes of true ecological restoration, rehabilitation, and reclamation of degraded ecosystems in terms of ecosystem structure and function (adapted from Bradshaw 2004). *Reclamation* reinstates, often rapidly, a biologically productive ecosystem. *Rehabilitation* establishes some type of vegetation cover and partially re-establishes ecosystem function. True *ecological restoration* leads to high ecosystem structure and biodiversity, as well as high ecosystem functioning. Due to increasing climate and global change, however, the historical reference system usually is not feasible, but different restoration options exist, where focus and aims may slightly differ. Hatched circles indicate that systems will be dynamic over time. *Unintentional degradation* (not depicted) occurs when restoration activities inadvertently damage or destroy ecosystems of high conservation value (e.g. afforestation of savannas; Veldman et al. 2015*a*).

forests. We suggest that FLR be rebranded as simply *landscape restoration*, to be inclusive of the diversity of Earth's biomes, many of which co-occur at the landscape scale.

Stepping Back: Changing the Narrative and Confronting the Global Biome Crisis

Important restoration initiatives with a focus on forests started before the Bonn Challenge. One prominent example is Brazil's Atlantic Forest Pact, a network of more than 260 institutions that aim to restore 15 million hectares until 2050 (Pinto et al. 2014). This initiative builds on the restoration experiences and research in the Atlantic Forest, the Brazilian biome that suffered the most severe habitat conversion in recent decades (Ribeiro et al. 2009). While Brazil's Atlantic Forest is indeed in dire need of restoration, we are concerned that there are no similar large-scale initiatives for Brazil's other biomes (e.g. Cerrado) or for non-forest ecosystems. Grasslands, savannas, and shrublands of Brazil are equally rich in biodiversity as forests and provide critical ecosystem services (e.g. Brazil's largest cities depend on watersheds in the Cerrado, and yet restoration research and application is lagging far behind [Overbeck et al. 2015]). We are concerned that as experiences, techniques, and funding for large-scale forest restoration become available (e.g. Alexander et al. 2011; Moreira da Silva et al. 2017), trees will be planted in possibly well-intended, but nonetheless ill-conceived, restoration projects (i.e., afforestation—Veldman et al. 2015*a* reclamation, or remediation; Fig. 1).

A further risk is that resources will be funnelled to only some of the habitats that have restoration needs, namely those for which techniques are available and where some economic interests or bureaucracies foster tree-planting activities (Fleischman 2014). Consequently and potentially increased by their sheer spatial scale, these projects will receive more attention from media and science, with the risk of forgetting other ecosystems where restoration demands and/or benefits may be as great or greater. Additionally, there is the risk that restoration knowledge and experiences from forests will be expanded to ecosystems where this kind of "restoration" is clearly not appropriate.

When it comes to conservation and restoration, the world's grassy biomes (including grasslands and savannas, and many peatlands and wetlands) are not, as it seems, as attractive or visible to the public, policymakers, and many scientists, compared to forests (Bond & Parr 2010). This is somewhat surprising given that grassy biomes are ancient, diverse, and culturally important landscapes that perform many ecosystem functions and provide many ecosystem services (including food security; Bengtsson et al. 2019). This applies to both tropical (Bond 2012; Veldman et al. 2015*a*; Pausas & Bond 2018) and temperate systems (Habel et al. 2013; Dengler et al. 2014). This blind spot for grassy biomes may have several causes, the first being that high conservation value grasslands are often subsumed into general land use categories such as "agricultural land" or "pasture," along with productive species-poor artificial grasslands, and hence tend to disappear from people's consciousness. A second reason may be the fact that a large part of the world's savannas and grasslands experience frequent "disturbances" such as fire and grazing by large, often domestic, animals (Bond 2012; Veldman et al. 2015*b*; Pausas & Bond 2018). Although grassy

biomes have similar global land cover to forests, there are fewer publications and restoration projects in grassy biomes (although this discrepancy is reducing over time). Peatlands cover a far lower percentage of the globe, but store the largest amount of C, such that focusing more on their restoration in temperate latitudes will be important since they have a lower susceptibility of C loss to warming than at higher latitudes (Crowther et al. 2016). However, peatlands receive much less attention than forests as target habitats for restoration (Fig. 2). As such, we clearly undervalue many mega-diverse biomes and habitats and easily transform them into cropland and urban areas (e.g. Searchinger et al. 2015). The lack of public recognition of the loss of non-forest ecosystems may stem from the perception that grassy landscapes are necessarily human-created, or at best semi-natural, thus disregarding their conservation values in terms of biodiversity, structure, functioning, and services. For example, we have lost around 50–70% of species-rich grasslands in central and northern Europe alone in the past 30 years, yet this is not known to the general public who are well-informed about tropical forest loss (Habel et al. 2013).

Equally importantly, we are losing vast tracts of biodiverse forests, savannas, grasslands, and peatlands at the same time as elsewhere we are striving to restore and conserve biodiversity and reach specific Aichi and Bonn Challenge targets (e.g. Tittensor et al. 2014). Examples for this include the Brazilian Cerrado (Noojipady et al. 2017) or the South American Gran Chaco (Baumann et al. 2017) that are massively affected by expansion of agricultural land for commodity production. Globally, 3.2 billion people are directly affected by land degradation (IPBES 2018). Over the last two centuries, competition for productive land has led to the clearing or conversion to agriculture of approximately 70% of the grassland, 50% of the savannah, 45% of the temperate deciduous forest, and 27% of the tropical forest (UNCCD 2013). By 2030, the demand for food, energy, and water is expected to increase by 50, 45, and 30%, respectively (UNCCD 2013), which will increase pressure to convert natural lands. Clearly, continued destruction of natural vegetation (including draining of wetlands and peatlands and concomitant massive greenhouse gas emissions) is "the biggest megatrend not pointing in the right direction" (Carrington 2017). Annual tree losses have nearly doubled since 2000, even though we know that destruction of forests for ranching, timber, and farming cause around 10% of the world's greenhouse gas emissions (Seddon et al. 2019).

Only about 2% of global climate finance (around $2.3 billion since 2010) is committed to forests. Brazil and Indonesia's governments alone invested $276 billion in the same time frame in just four key driver commodities: palm oil, soy, beef, and timber (Wolosin et al. 2016). In contrast, in the Paris Agreement, 42% of signatories include afforestation and/or restoration of forests as components of their nationally determined contributions (NDCs), compared with only 19% for coastal habitats (in countries with coastlines), and grasslands in only 8% of NDCs (Seddon et al. 2019). Clearly restoration investments are occurring based on the assumption that trees equate with conservation rather that evenhanded assessments of the restoration value of ecosystems based on antiquity, biodiversity, ecosystem functions, and services (including C storage), and not by whether they appear to be "natural" or not. Indeed, many hyper-diverse forests, even in the tropics, show strong traces of human influence (Levis et al. 2017). The fact that temperate grasslands, savannahs, shrublands, and Mediterranean woodlands and forests have higher conservation risk index ratios compared to tropical, temperate, and boreal forests, deserts, or tundra (Hoekstra et al. 2005; UNCCD 2013) clearly shows that open, grassy and shrubby biomes are not getting the protection or restoration they need. As a consequence, there is a vast untapped potential to improve both their conservation (via changes to their protection) and restoration through more explicit inclusion in the Bonn Challenge and other science-policy platforms (Seddon et al. 2019).

Where to Restore What Type of Habitat?

We suggest that the ambitious goals of the Bonn Challenge can only be met with concrete restoration and rehabilitation actions developed to include the diversity of Earth's ecosystems. We must protect biodiversity in all biomes and adjust land use to reduce land degradation towards land degradation neutrality (LDN; Cowie et al. 2018). To this end, we need to clearly consider the where and what to restore, as well as define the activities that we consider to be ecological restoration as opposed to rehabilitation or reclamation (Fig. 1).

The Society for Ecological Restoration (SER) defines ecological restoration as: "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed." What is often termed *true restoration* aims for high ecosystem structure and biodiversity, as well as high ecosystem functioning, in contrast to rehabilitation of a degraded ecosystem that mainly focuses on reinstating ground cover and some level of ecosystem functioning or service. Reclamation, on the other hand, involves replacing and stabilizing the degraded ecosystem by biologically productive, often intensive systems (croplands, improved pasture) that may provide one particularly desired ecosystem service but lack biodiversity and all its manifold effects on functioning and services (Bradshaw 2004; Yang et al. 2019). However, when striving for true restoration in times of global change, there is a need to assess shifting baselines for ecological restoration, including what our target communities are, as reaching historical reference ecosystems may no longer be possible. This underlines the need to systemically study to what extent we can send communities on trajectories in the direction of historical targets (or with similar indicator species) and what range of different of alternative species-rich and well-functioning communities that are adapted to expected future climate are also possible in different regions (see Fig. 1). This is an area that urgently needs more research and regional landscape-scale restoration projects to answer such crucial questions.

We argue that wherever possible we should aim for ecological restoration (see Fig. 1) since it usually promotes the greatest biodiversity and ecosystem functioning (Benayas et al. 2009; Isbell et al. 2011; Yang et al. 2019). Nonetheless, in light of climate change and eutrophication of many regions of the world,

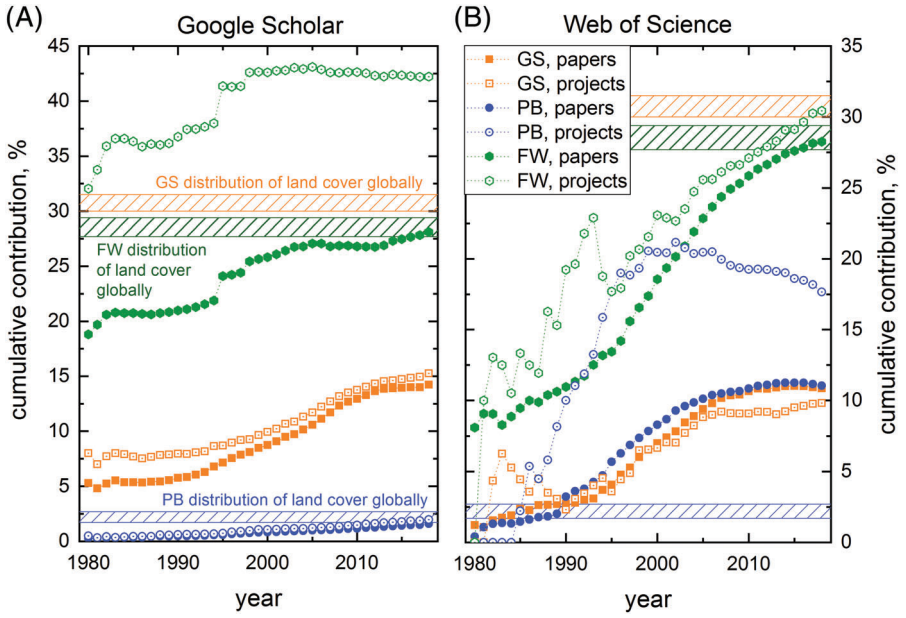

Figure 2. Cumulative contribution of ecological restoration publications and projects over time since 1980, as found in (A) Google Scholar and (B) Web of Science, separated into major habitat types (PB—peatlands bogs and wetlands; GS—grasslands and savannas; FW—forests and woodlands). Note the dashed lines show percentage of total global land cover for each category. Also note that C storage capacity is much higher for peatlands, followed by forests, then grasslands; however, if C residence time is considered this ranking would change again (see text for details). Given that grasslands and savannas provide as wide an array of ecosystem services as forests (Bengtsson et al. 2019), this suggests that we undervalue landscapes that are maintained by frequent disturbances (e.g. fire and herbivory). The search in Web of Science indicated a large difference between number of peatland projects and publications that was not found using Google Scholar. FW, forest and woodland; GW, grasslands and savannas; PB, peatland and wetland projects. Search terms were either *(restoration OR restored) AND (eco* OR ecol*) AND (…)*, or *(restoration OR restored) AND (eco* OR ecol*) AND (project*) AND (…),* where *(…)* remained blank or was the name of the biome, i.e. *(grassland* OR grassy OR savanna*)*, *(peatland* OR bog* OR wetland*)*, or *(wood* OR woodland* OR forest*)*.

the call for flexible targets for ecological restoration is more important than ever (Harris et al. 2006; Choi 2008; Suding 2011; Aronson et al. 2018; Higgs et al. 2018). At the same time, at the landscape scale we should aim to ensure that as many species typical of different historical ecosystems are included in the restoration projects to allow for natural assembly to filter out those most adapted to the current and predicted future conditions. Assisted migration, whereby species are translocated to sites that are predicted to suit their ecological niche better in the future (Hewitt et al. 2011), despite being controversial, will no doubt gain in importance as many biomes gradually merge into one another (e.g. tropical forests into savannas as predicted by Intergovernmental Panel on Climate Change climate models).

To assess whether there is evidence for a bias towards forest restoration in the scientific literature and or in restoration projects, we performed a literature search in Web of Science and Google Scholar. Figure 2 shows ecological restoration projects and scientific publications according to the three ecosystem categories "Forest and woodland," "Peatlands and bogs," "savannas and grasslands", and in relation to global land cover of each category. It portrays the preponderance of forests and peatland restoration projects in comparison to grassland and savannah restoration. Interestingly the number of publications on grassy habitats is similar to the number of restoration projects, whereas projects far outnumber publications for the forest and less so peatland habitats.

It is also important to be clear about our definition of what constitutes a degraded habitat. Hobbs (2016) correctly focuses on the key question of how exactly we decide and measure whether a site is degraded (a decision which forms the basis for all ecological restoration actions). He writes: "Decisions to 'restore' areas to alternative ecosystem types are often taken on the basis of perceptions of what was there, or what 'should have been' there, rather than a consideration of the relative value of the existing system and the costs versus benefits of the restoration." We propose that focusing on biodiversity (including species, functional and habitat diversity) and applying a conceptual approach in decision-making such as LDN (Cowie et al. 2018) could help solve this issue. LDN aims to stop overall net land degradation or even to reduce degradation by addressing land use and changes in land use at whole landscape regional scales, while taking biodiversity into account (O'Farrell & Anderson 2010).

Working at the landscape scale necessarily also means considering the multifunctionality of landscapes. This is also advocated within FLR (Chazdon et al. 2017), but their form of multifunctionality seems to be restricted to tree-dominated and forest restoration actions and misses the potential of widening the suite of biomes and options leading to what we term *strong multifunctionality* as it operates on several scales, both within and between habitat and land use types. We define strong multifunctionality in the sense of *strong sustainability* (Ekins et al.

Table 1. For the Bonn Challenge to create true win-win outcomes and be successful both as a means to restore biodiversity and to cool the climate (not just to store more C) it requires concerted and inter- and transdisciplinary efforts, including strong restoration science, practice, and communication to develop an inclusive strategy for ecological restoration and greenhouse gas drawdown from the atmosphere.

Science Needs	Practice Needs	Communication Needs
Clear definitions and criteria to identify ecosystems as degraded to avoid erroneous interpretation of non-forest systems as degraded forest that may then be subject to "reforestation"	Inclusion of habitat and biodiversity safeguards into large-scale restoration projects, especially those with funding from REDD+ or other mechanisms	Stepping back and opening up the overall conversation to natural climate solutions that include a range of different habitat types
Assessment of ecosystem capacity to sequester as well as retain C, *above- and belowground*, over a large range of ecosystems, as well as assess other processes that influence climate (albedo, VOC, etc.)	Development of infrastructure for seed/seedling production and of restoration techniques for ecosystems previously neglected in restoration	Communicating that policy frameworks such as the Bonn Challenge are major opportunities to address the biome crisis and stem biodiversity loss, by giving due attention to temperate and tropical grasslands and savannas that have experienced the largest loss of habitat over the past 30 years (Hoekstra et al. 2005).
Assessment and modelling of ecosystem functions and services and their trade-offs within large-scale restoration (C storage in AGB × biodiversity, C storage in AGB × water provisioning)	Assessment and modelling of ecosystem functions and services and their trade-offs in large-scale restoration (including monitoring water yield at watershed level over time, as well as C storage, mitigation of warming, provisioning ecosystem services)	Showing that C storage is a diffuse ecosystem service (local intervention for global benefit), while water provisioning brings local benefits (local intervention for local benefit). Acknowledging that the trade-off between them is problematic in seasonally dry climates (zones under risk of afforestation).
Development of useful indicators for restoration success that can be easily applied on the ground but deliver integrated information	Monitoring of collective benefits (biodiversity, climate mitigation, and livelihoods) of FLR projects	
	Adaptive management of restoration projects	

AGB, aboveground biomass

2003) to include socioeconomic sustainability that does not compromise the biophysical (biodiversity-driven) relationships on which livelihoods depend. This goal is possible with a mosaic of different land uses including extensively—and sometimes intensively—managed open landscapes next to more protected habitats (see papers on sustainable multifunctional landscapes; Fry 2001; Lovell & Johnston 2009; O'Farrell & Anderson 2010). Thus landscape-scale strong multifunctionality does not occur at the overall expense of one habitat, species, or functional richness but includes them. Strong multifunctionality will not always be a realistic goal, but wherever possible the chances of it being reached should be adequately assessed within science policy.

Stepping Up to Create a Broad Scientific Basis for Large-Scale Biodiversity Restoration and Climate Mitigation

Enabling science and research to "catch up" with policy will involve a concerted effort on the part of scientists and funding agencies to make sure that the key issues brought up by the policy drive are backed up by the best possible and broadest scientific evidence (McNie 2007; Posner & Cvitanovic 2019). This will need to include both an explicit integration of available knowledge as well as addressing remaining knowledge gaps with new research (see Table 1 for an overview of suggested activities). At the same time, catching up will require a second, equally important component of effective, open, and adaptive communication and decision-making between the many stakeholders involved, based on the best possible scientific evidence (Suding et al. 2015; Fig. 3). In some cases this will lead to true win-win outcomes, restoring biodiversity, mitigating warming, increasing resilience to extreme weather events, and fostering strong multifunctionality. In other cases, this may not be possible, and we will need to decide which ecosystem services we are mainly aiming for (including water yield, carbon, food security, soil erosion control, wood or hay harvest; Fig. 3). To reach a level where we differentiate between win-win scenarios and trade-off situations requires concerted interdisciplinary research. A possible best practice here could include larger scale landscape planning, with a mosaic of different land uses and habitats in an area (Tong et al. 2006; Jonson 2010; Chazdon & Laestadius 2016), but with each land use having been assessed for optimum ecosystem service outcomes. A science-based approach could include a set of embedded experiments at landscape scale (Gellie et al. 2018). Here, we identify four key areas that require interdisciplinary and partly transdisciplinary research to step up to the plate.

Stepping Up Part 1: The Climate Cooling Story, More Than Just Carbon Storage

Natural or nature-based climate solutions include a variety of different components: reducing climate warming (via changes in radiative forcing), resilience adaptation to altered disturbance regimes, as well as increasing longer term carbon stocks (C already present in an ecosystem) and sequestration (rate of new C removal from the atmosphere). Planting trees and reforesting/afforesting sites have generally emerged as a highly popular natural climate solution (Griscom et al. 2017; Popkin 2019; Seddon et al. 2019). This makes intuitive sense, since trees, being woody, store vast amounts of carbon as lignin in their trunks and hence are seen as the preferred fast track to store carbon above- and belowground in vast quantities, particularly in tropical and subtropical regions where the climate

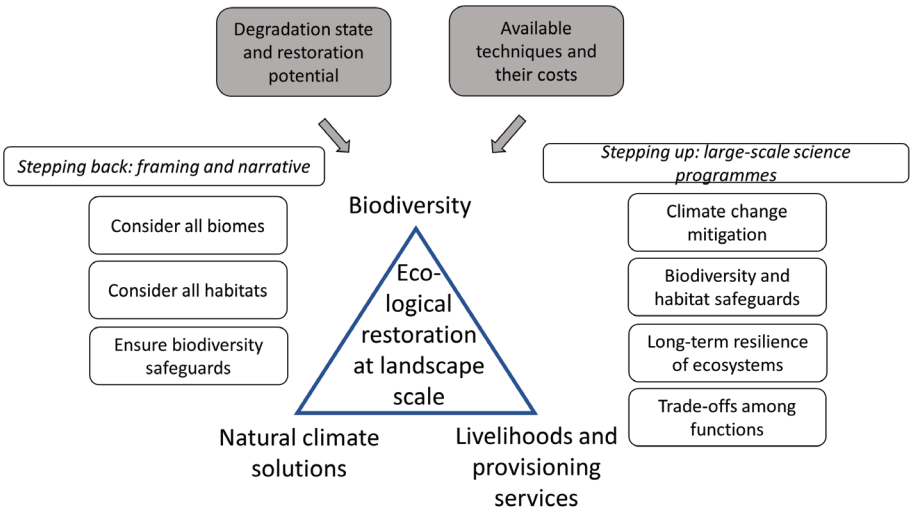

Figure 3. Restoration of ecosystems at a landscape scale should maximize three objectives: biodiversity, natural climate solutions, and livelihoods and ecosystem services. Stepping back involves consideration all types of biomes and habitats. Stepping up requires improved scientific study of ecological restoration on a landscape scale (Perring et al. 2018). Key areas for research include assessment of which restoration actions best deliver bundles of ecosystem services without compromising the biophysical relationships that regulate these services. In particular the relative benefits of restoration with native versus non-native species requires concerted and integrative research and practice efforts.

allows for very fast growth. National estimates of C loss and gains, using field plots and satellite data, conclude that forests are globally a large C sink, removing more C out of the atmosphere than they release through respiration and decomposition (Pan et al. 2011). Recent research urges caution that "forests have many more complex and uncertain climate impacts than policymakers, environmentalists, and even some scientists acknowledge" (Popkin 2019). In particular it is as yet uncertain whether volatile organic compounds (VOCs) such as terpenes (e.g. in boreal forests) and isoprenes (in temperate and tropical forests) emitted from forests contribute to cooling or warming the planet—and this may depend on the geographical location and type of forest (Unger 2014; Scott et al. 2018). Clearing forests releases C stored in trees but it increases the Earth's albedo (reflection of solar radiation back into space) such that we now need scientific assessments of whether this leads to net cooling or warming. Luyssaert et al. (2018) assessed trade-offs in using European forests to meet climate objectives, and found that improved C sequestration may be offset by changes in surface albedo, land surface roughness, VOC emissions, transpiration, and sensible heat flux induced by different forest management. Understanding the extent to which C sequestration through restoration within FLR can cool the planet will therefore depend on the net interplay of carbon uptake and VOC emissions, as well as albedo and transpiration differences between forest types and between different biomes. Clearly, there are urgent research needs to develop these overall balances for different regions where currently FLR is of high relevance.

If one considers the longer term, and more detailed facets of carbon sequestration such as carbon turnover times, long-term belowground carbon or albedo effects, then other biomes can sometimes deliver equally or better climate benefits than forests. High-latitude afforestation, e.g. will accelerate rather than mitigate climate change via reduced albedo (Bala et al. 2007). Thus we need to assess whether and which type of reforestation makes the most sense in which regions, and where other ecosystems (e.g. savannas) are better climate coolers. Under a changing climate that is expected to bring about changes in fire and precipitation regimes, grasslands may actually prove to be more secure carbon sinks than forest, as has been demonstrated in semi-arid California (Dass et al. 2018).

If we are serious about storing more C we need to consider C turnover, or mean residence time of C in different habitat types, that is, how long the C stays in the system (in the soils and the vegetation). Carvalhais et al. (2014) analysed C turnover times at the global level and across biome types and found that the average global C turnover time is 23 years, with large variation at different latitudes (15 years near the equator vs. 255 years beyond 75° north), driven by precipitation and temperature differences. Boreal forests and tundra store the most for the longest time, whereas tropical forests and savannas store C for the shortest time. Although tropical and boreal forests store by far the most C overall (C stocks), temperate shrubland and grasslands, boreal forests, tundra, and deserts had the longest C turnover times (between 40–60 years versus less than 20 years for tropical and temperate forests; Carvalhais et al. 2014). Again, albedo complicates matters, since in boreal forests cooling from C storage is more than offset by warming from reduced albedo; for this reason Griscom et al. (2017) did not consider restoration of boreal forests as an option for nature-based solutions.

We also need to consider the role of altered disturbance regimes on C turnover times. Recent major forest fires suggest that, in California, increased fire frequency and intensity as well as higher tree mortality could wipe out any forest restoration gains very quickly (Dass et al. 2018). Using more prescribed fire may help: Wiedinmeyer and Hurteau (2010) found that prescribed fire maintained C below potential on any given

site but that residual C was more secure and less susceptible to loss in wildfires. Warming itself will influence the global C cycle, with scenarios that predict a net release of C into the atmosphere, particularly in high latitudes (in the form of methane) that will further accelerate climate change (Crowther et al. 2016; Matthews et al. 2018). Charcoal produced by fires, and either incorporated into soil or transported off-site, is highly resistant to oxidation and methanogenesis, and represents a critical long-term carbon storage pool (Reisser et al. 2016).

When focusing on C sequestration, we highlight the need for a concerted and (where possible) standardized scientific assessment of C storage and fluxes within and between different habitat types, based on a large already available reservoir of datasets. Large-scale C cycling projects such as the integrated carbon observation system Research Infrastructure (Franz et al. 2018) or the National Ecological Observatory Network (Loescher et al. 2017) have a wealth of data on net ecosystem productivity, partitioned gross primary productivity, and total ecosystem respiration, as well as net biome productivity that includes lateral losses from ecosystems due to fire and leaching. Although there is a plethora of research on carbon storage in different biomes and habitats, there are as yet few meta-analyses that explicitly compare the aboveground and belowground carbon storage capacities of different habitat types, including mean residence times of carbon that would allow for a better discussion of trade-offs e.g. between biodiversity, carbon storage, water provisioning, and other ecosystem services in conservation and restoration decisions. Overall, there is now the need to assess the multifaceted components of climate warming or cooling by explicitly researching and including resilience adaptation (including considering increased tree mortality and fire disturbance), C residence times, and effects of VOCs and albedo as well as C storage.

Stepping Up Part 2: The Need for Biodiversity and Habitat Safeguards

All aspects of human development, including economic welfare and social equity, ultimately rely on basic processes of the Earth system. True sustainability is based on the understanding that we only have one Earth and that the different planetary boundaries are interdependent (Steffen et al. 2015). While multiple goals, including those more related to social and economic aspects, are essential to ecological restoration (Ekins et al. 2003; Aronson et al. 2018; Higgs et al. 2018), it is the biophysical quality of the (restored) environment, with its many aspects, including biodiversity, that guarantees long-term restoration success as well as the provision of benefits for humans (Díaz et al. 2018) where ecosystem services are renamed *nature's contributions to people*. In a recent debate about biodiversity safeguards and how open and flexible ecological restoration needs to be, Higgs et al. (2018) and Aronson et al. (2018) seem to essentially agree about the need for having biodiversity safeguards. "Restoration is positioned to become a go-to approach for addressing future environmental challenges [...] and this must bring with it a signature commitment to ecosystem integrity" (e.g. biodiversity safeguards; Higgs et al. 2018). Aronson et al. (2018) advocate restoration as the means to "reinstate biological integrity." Where they disagree, it seems, is on whether the target communities for restoration should be based on pre-existing communities or a combination of the past and the future. No matter what our restoration targets are, we suggest that scientists must more clearly elucidate the biophysical basis for resilience (including the key role of biodiversity) in the face of a globally changing world. Policy and management decisions that affect the provisioning of livelihoods and sociocultural services must be based on biophysical realities (Díaz et al. 2018).

Thus we need to agree at a minimum on clear biodiversity safeguards as a basis, not as a an equal or disposable bargaining chip in the process of setting goals for sustainability including for restoration and climate mitigation programmes such as the Bonn Challenge. Research on interactive effects of different global change drivers (nutrient excess, biological invasions, extreme weather events) on biodiversity and ecosystem functioning shows that the outcome can be additive, antagonistic, or synergistic (Zavaleta et al. 2003; Meyer-Grünefeldt et al. 2015). Clearly more research is needed on not just one global change driver but on several at once. In light of this complexity, and as science catches up with restoration policy, a conservative approach to biodiversity safeguards would involve future focused restoration guided by certain aspects of historical communities but considering climate model predictions (Choi 2008).

The question of which species to restore where is also central if one aims to mitigate climate change and restore biodiversity and livelihoods. Pioneer and sometimes invasive non-native trees are commonly used in "restoration" projects where species-rich grasslands were afforested, causing impacts on biodiversity and ecosystem services. For instance, from 1999 to 2010, as part of the Grain for Green Project developed to prevent soil erosion in China, 79.3 million hectares of grassland and cropland were planted with non-native trees, accounting for 46% of the 2010 target (Uchida et al. 2015). Afforestation using non-native trees such as *Robinia pseudoacacia* and *Prunus armeniaca* in arid and semi-arid grasslands resulted in ecological degradation due to decreased soil moisture and the removal of natural herbaceous vegetation (i.e. grasses, forbs, herbs) to promote tree growth. The number of plant species at the afforestation site decreased by an average of 52% by the seventh year after planting (Cao et al. 2010, 2011). Grassy biomes can represent "an inconvenient reality" for large-scale tree-planting efforts, since afforestation leads to biodiversity loss (Veldman et al. 2017) as well as reduction in albedo. Thus, it is imperative that we include the biodiversity of habitats when considering natural climate solutions, including taking into account what the predominant surrounding land use has been in the recent past. This will enable us to tackle the biome crisis (see Box 1) while creating sound climate solutions. The extent to which restoration reinstates species interactions is currently an emerging field, especially for plant-pollinator interaction webs (Forup et al. 2008; Dixon 2009). Future research should focus on the relative ability (and availability, see Table 1 Practice Needs column) of native versus non-native as well as invasive plant species (whether native or not) to reinstate complex webs of

interactions. There is a need for larger scale integrative restoration research (Perring et al. 2015, 2018) to address these key issues at the nexus between biodiversity and climate change.

Box 1. Glossary of important concepts and definitions.

Aboveground carbon storage: Total aboveground dry matter biomass of live and dead vegetation.

Belowground carbon storage: Soil organic matter plus dry matter biomass of underground plant organs (e.g. roots).

Aboveground/belowground carbon sequestration: Rate of new carbon stored minus carbon lost (e.g. annual net primary productivity).

Biodiversity safeguards: Cautionary requirements to ensure that ecological restoration does not harm biodiversity (Phelps et al. 2012). Harm can occur if "restoration action" replaces species-rich native vegetation with monocultures or invasive species of low conservation value.

Biome crisis: The rapid loss of natural ecosystems due to conversion to intensive human land uses or urban development. Whereas some biomes are relatively well protected, others are experiencing widespread conversion. A habitat conversion risk index (Hoekstra et al. 2005) highlights large discrepancy in our valuing of different biomes, which has also contributed to the biome crisis. Habitats with a large risk of habitat conversion and with limited habitat protection (e.g. species-rich grasslands and savannas, Mediterranean biomes) are often undervalued for the ecosystem services they provide (Bengtsson et al. 2019).

Ecological restoration: "Ecological restoration is the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Clewell et al. 2004). A similar definition was adopted by the El Salvador Initiative that was the basis for the Declaration of the UN Decade of Ecosystem Restoration 2021–2030: "Ecosystem restoration is understood as assisting the recovery of degraded, damaged and destroyed ecosystems to regain ecological functionality and provide the goods and services that people value." Note the omission of the word biodiversity and the wording "services that people value" here. This definition is problematic as it is not inclusive of biodiversity safeguards (see Figs. 1 & 3). In addition, since nature provides many services, of which many people are not aware, we propose writing instead "and provide goods and services of value to people." Within a sustainability and climate change framing, it will become increasingly important to include the idea of future value as a form of resilience and justice between generations (Griggs et al. 2013).

Forest and Landscape Restoration (FLR): The main programme behind the Bonn Challenge, which has evolved from being called Forest Landscape Restoration to Forest and Landscape Restoration. The landscape component of the title begets the question of whether all other habitat types are included here next to the forests, or whether the word landscape applies to a larger systems approach that includes different components of the landscape. Even if it were the latter, the question why one would mainly focus on forests and trees arises, given that open habitats can also store carbon for long periods of time and provide high albedo. The current focus seems to assume that forest restoration will be more efficient in reaching multiple restoration goals than restoration of other types of habitat, e.g. steppe or savanna landscapes (that may also contain forest elements). This assumption has not yet been scientifically demonstrated and requires concerted research programmes at national and international level.

Multifunctionality: Taking a wide array of functions into consideration when studying the relationship between biodiversity and ecosystem functions and services. In particular, not merely focusing on provisioning but also regulating and cultural services, is a natural consequence of using a multifunctionality framing. A multifunctional perspective is essential for ecological restoration that seeks to promote biodiversity conservation, climate change mitigation, ecosystem services, and human livelihoods. Restoring multifunctionality requires an interdisciplinary assessment of the different functions in a landscapes and their trade-offs (see e.g. Bolliger et al. 2011).

Natural climate solution: "Conservation, restoration, and improved land management actions that increase carbon storage and/or avoid greenhouse gas emissions across global forests, wetlands, grasslands, and agricultural lands" (Griscom et al. 2017). Which habitats will form the best natural climate solutions will depend on carbon storage as well as a better understanding of which vegetation types actually contribute to cooling the climate, taking albedo and VOC emissions into account.

Landscape restoration: Landscape restoration values all types of biomes and habitats in need of restoration. It is important to recognize that most landscapes consist of mosaics of different habitat types. In order to guarantee restoration of biodiversity in complex landscapes, multiple co-occurring ecosystems need to be considered as a whole.

Stepping Up Part 3: The More, the Merrier, Biodiversity Begets Functioning and Often Also Services

In the midst of the sixth mass extinction, ecologists have increasingly focused their attention on the question of the consequence of biodiversity loss for ecosystem functioning. A plethora of smaller scale and an increasing number of large-scale, long-term experiments have been set up to test the effects of plant biodiversity on ecosystem functions, so-called Biodiversity Ecosystem Functioning (BEF) experiments (Roscher et al. 2004; Bruelheide et al. 2014; Weisser et al. 2017). The main outcome of these experiments is that higher species and

functional diversity of plant species leads to improved ecosystem functions such as productivity, nutrient cycling, microbial biodiversity, and carbon storage (Lange et al. 2015; Thakur et al. 2015), pollination and other functions. Rather unsurprisingly, with increasing plant biodiversity the diversity of other trophic levels also rises, and this holds true for aboveground as well as belowground taxa (Scherber et al. 2010). Such research outcomes hold much promise for application in conservation and restoration, since planting higher species and functional diversity could have many ramifying multifunctional effects (Montoya et al. 2012).

Positive biodiversity effects in grasslands differ in speed between the aboveground and belowground, where e.g. higher plant species richness and functional diversity lead to more root biomass, but only after an initial time lag of 4 years (Ravenek et al. 2014). The time lag suggests that belowground interactions and reaction speeds are more buffered here than for the aboveground, which could have an effect on potential speed of belowground C sequestration during grassland restoration (but see Yang et al. 2019 for the impressive potential for this). The positive biodiversity effect in grasslands sets in aboveground in the first year and becomes magnified over time as nutrients are removed from the system with mowing (Marquard et al. 2009; Meyer et al. 2018), thus fostering facilitative interactions in relation to nitrogen (Roscher et al. 2011). One of the mechanisms is that biodiversity effects increase in diverse species mixtures compared with poorer performance over time in monocultures due to negative density-dependent plant soils feedback (Cortois et al. 2016; Meyer et al. 2016).

Importantly, analyses of a wide range of BEF experiments in grasslands have shown that many species are needed to allow for multifunctionality over longer periods of time (Isbell et al. 2011) and that more diverse systems are more resistant to increasing climate change perturbations (Isbell et al. 2015). Additionally, while dominant species often disproportionately drive the ecosystem functioning in 1 year, there is often high turnover between years, that is different species will drive functioning each year (Allan et al. 2011). This is very different to comparisons between a monoculture eucalypt plantation and species-rich forests, where trees cannot quickly change their dominance within a community as quickly as herbaceous species, but also where secondary compounds within eucalypt trees may be cancelling out negative plant soils feedback effects of growing on the same site for longer periods.

Recent BEF experiments in forests, however, are confirming that biodiversity matters for functioning in tree-dominated systems too (Potvin & Gotelli 2008; Fichtner et al. 2018; Huang et al. 2018). Potvin and Gotelli (2008) found that higher tree diversity in a tree plantation in Panama led to higher productivity but did not affect survival of the trees. In the BEF China project, Huang et al. (2018) found that species richness strongly increased stand-level productivity and after 8 years in 16-species mixtures. In terms of C, 16-species mixtures had accumulated over twice the amount of carbon found in average monocultures and similar amounts to those of two commonly used two commercial monocultures. Very few studies so far have attempted to compare the effect sizes of biodiversity effects across different habitat types (grassland, forest, wetland), possibly since the number of studies in wetlands is still limited compared to grasslands, and the tree experiments are still generally in their infancy. Such an analysis of overall effect sizes as well as coordinated experiments and/or meta-analyses involving different biome types would be a major gain in the future.

Overall, the evidence strongly suggests that if we want to have well-functioning ecosystems that can be resistant or resilient especially in the face of climate change (Jaeschke et al. 2014), we need to strive to have as many species with as many traits that differ from each other as possible in an ecosystem. Experiments that test the relevance of BEF outcomes for restoration have found that sowing more diverse seed mixtures (Bullock et al. 2001, 2007) or altering the order of arrival of plant functional groups (Weidlich et al. 2017*a*, 2017*b*) can lead to more productive but also diverse plant communities. This is an asset within extensively managed grasslands, since higher biodiversity is usually mutually exclusive to provisioning of crops and commodities in intensive agriculture (Cord et al. 2017). Overall, BEF research as well as assessments in natural systems indicate that having more species with a wide range of different traits in an ecosystem is advantageous for ecosystem functioning and services (except perhaps for provisioning services). This relationship holds particularly well in times of highly variable abiotic conditions, such as we are experiencing under climate change. Further research needs to integrate BEF research across different habitats and biomes, and test the extent to which positive biodiversity effects act in the real world (Poorter et al. 2015; Buchmann et al. 2018; Schulze et al. 2018). In addition, the extent to which non-native species can deliver positive biodiversity effects across trophic levels needs concerted research attention.

Stepping Up Part 4: Watch Out for the Trade-Offs

A key issue that needs to be adequately addressed within the Bonn Challenge is how best to deal with the multiple goals of FLR projects, their inherent multifunctionality, and how they deliver different ecosystem services. Systematic and integrated assessment of the collective benefits of FLR in terms of biodiversity, livelihood, and climate mitigation outcomes (Chazdon & Laestadius 2016; Mansourian 2017) will provide a better basis from which to adaptively manage action on the ground. Holistically assessing performance outcomes is an area that therefore urgently needs concerted attention and investment of resources (Suding 2011; Perring et al. 2015, 2018; Chazdon et al. 2017). Only once we have enough data on this topic can we adaptively adjust our actions and start effectively prioritizing where and which processes and actions are most important (Suding 2011; Perring et al. 2015) for different desired biodiversity, ecosystem functioning, and service scenarios. Scientific research will play an essential role in focusing and delivering evidence-based knowledge to back up this larger process (as seen by recent publications cautioning that storage carbon alone does not necessarily stop climate warming; e.g. Unger 2014; Luyssaert et al. 2018).

Our approach is in line with much of that proposed by Chazdon and colleagues (Chazdon & Laestadius 2016; Chazdon et al. 2017) as necessary for successful FLR, with some essential differences: it is framed with the need for aiming for ecological restoration wherever possible (see Fig. 1), as opposed to rehabilitation or reclamation. In addition, we advocate action in as many habitat types as possible, that include biodiversity safeguards, such that biodiversity restoration is one of the main goals of a project.

There are often clear trade-offs between provisioning versus regulatory and cultural ecosystem services (Deng et al. 2016; Cord et al. 2017). This is illustrated by the relationship between carbon storage and water yield. While biodiversity and carbon today often dominate the restoration debate, the additional benefits of forest and forest restoration for hydrological cycles and for water discharges for human use are often also emphasized. Many forest ecosystems are indeed a critical component in regional moisture recycling processes, such as the Amazon forest that influences rainfall patterns in southeastern South America (Zemp et al. 2014). However, the much-cited contribution of forest restoration to water provisioning (i.e. increase in water run-off in rivers) requires critical evaluation. A number of studies are finding that in the majority of cases we may have to make hard choices between the ecosystem services carbon storage and water provisioning when restoring forests (Jobbágy & Jackson 2000; Filoso et al. 2017). Honda and Durigan (2016) showed, for a Cerrado savanna in southwestern São Paulo State, Brazil, that in seasonally dry regions increased woody species cover reduces water available for uptake by plants and for recharge of rivers and groundwater reserves. In semiarid and arid regions in China where large-scale restoration projects with tree plantings have been carried out, soil resources and vegetation cover deteriorated and the groundwater level was actually decreased by tree plantings (Cao et al. 2011; Li et al. 2017). On the basis of classic hydrological studies on paired catchments (reviewed in Brown et al. 2005) changing forest cover in more than 20% of the area of a watershed will cause significant changes in water yield. Clearly, the claim that tree plantings or forest restoration increase water provisioning is rarely true and demands our concerted attention both in terms of more science and more inclusion of the outcomes in policy decisions.

"Trading water for carbon" (Jackson et al. 2005) through increased tree biomass is but one of the trade-offs to be considered. It is important to realize that tree planting and forest restoration are not always beneficial for biodiversity. For instance, in the Brazilian savanna, long-term fire suppression leading to woody species and forest encroachment, caused the species richness of both plants and ants to decline to the order of 30% (Abreu et al. 2017), and the richness of savanna specialists was affected even more strongly. This shows that the tree-focused approach of FLR is not an adequate restoration strategy in non-forest systems, if we aim at ecological restoration in the strict sense (Fig. 1) that aims at recovery of the ecosystem structure as well as the functioning of the ecosystem. In particular, species adapted to specific habitats (needing particular abiotic conditions, e.g. light availability) form a high proportion of biodiversity worldwide. FLR emphasizes the multifunctionality of its approach by claiming that "a combination of forest and non-forest ecosystems, land uses, and restoration approaches can be accommodated within a landscape to achieve sustainable food production, ecosystem service provisioning, and biodiversity conservation" (Chazdon et al. 2017). We suggest that, in many landscapes, non-forest ecosystems be given as much or higher priority than forests. Otherwise we risk supporting "restoration" that neither safeguards biodiversity nor mitigates climate change.

Assessment of multifunctionality and trade-offs in the provisioning of different ecosystem functions and services is of critical importance in landscape-scale restoration programmes. This will require inter- and transdisciplinary approaches to address and to maximize multifunctionality at the landscape scale. Patch mosaics, where certain land uses or restoration activities will promote certain services more than others, are a possible solution to an otherwise intractable problem, as long as biodiversity safeguards are considered across the whole landscape.

Conclusions: The Framing and Science Now Necessary to Back Up and Inform the Bonn Challenge

In order to ensure that the outcomes of restoration actions performed within the framework of the Bonn Challenge lead to true win-win outcomes in terms of biodiversity restoration and climate mitigation, we need to step back in our framing and to step up in our science. With biodiversity as the basis of a well-functioning system over time (as outlined above), a safeguard for biodiversity, at both the species and ecosystem levels, seems especially important. This would also allow us to address the biome crisis while also mitigating climate change.

In the vein of the SER Standards (Mcdonald et al. 2016) native recovery star system, one could imagine setting up criteria for assessing the relative merits of different restoration projects within a larger programme. The system should strive to be inclusive of a range of different ecosystem services and aim for multifunctionality wherever possible, considering nature's benefits to people in an integrative way (Díaz et al. 2018). In a landscape context it would make sense that a certain percentage of projects strive for the highest biodiversity ratings, whereas others may have other ecosystem services as their main focus. This could include extensive, intensive, and protected land uses and could also be developed based on the relative proportion of different types of habitat in the landscape that need restoration, that is include a habitat safeguard. Receiving full funding could then depend on the biodiversity and ecosystem service outcomes and their relative proportions. If the biophysical basis for sustainability were not maintained or restored, the economic or social goals may swamp the biodiversity goals, which may endanger the effective functioning of the ecosystem, such that we may lose out on synergies to be gained from increasing biodiversity for resilience, livelihood, and climate mitigation outcomes.

On the other hand, it is clear that we have immense knowledge gaps regarding the best way to reach multiple restoration goals, especially regarding the best ways for climate change

mitigation which, as discussed earlier, depends on a diversity of interactions among different processes whose relevant role will differ greatly in different biomes and habitats. Despite recent advances in the science that underpins ecological restoration (Temperton et al. 2004; Bullock et al. 2006; Walker et al. 2007; Roberts et al. 2009), having ecological restoration move this swiftly onto the global stage will require considerably larger efforts and assessment of what works best where, and to whom benefits accrue (Suding 2011). Large-scale science programmes that systematically assess the trade-offs associated with rehabilitation versus restoration and among the different restoration objectives in the long term (allowing for natural dynamics of ecological communities) are important next steps. These will provide a sound scientific basic for restoration at the landscape level such that we can optimize the diversity of habitats, livelihood options, and natural climate solutions (see Table 1 and Fig. 3). Strong research integration as well as bringing together multiple stakeholders as a means to optimize sustainable multifunctionality will be necessary (O'Farrell & Anderson 2010; Fig. 3). However, despite the need to also gather long-term data, there is a clear urgency to act now in reaching the multiple goals aimed at in the Bonn Challenge and in global commitments formulated, e.g. in the Paris agreement, the convention on biological diversity, and the sustainable development goals (SDGs). Restoration actions should be undertaken based on the best available scientific basis, and then monitored and adapted to ensure best possible outcomes.

The Bonn Challenge and the UN Decade on Ecosystem Restoration need concerted action if they are to meet the goals of the Paris Agreement, Aichi biodiversity targets, and the SDGs. We strongly advocate an inclusive perspective that will advance the restoration of many ecosystem types (not just forests and trees), conserve existing natural habitats, allow us to address the biome crisis, which is the primary driver of biodiversity loss, and offer hope of resilient ecosystems for human livelihoods.

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LITERATURE CITED

Abreu RCR, Hoffmann WA, Vasconcelos HL, Pilon NA, Rossatto DR, Durigan G (2017) The biodiversity cost of carbon sequestration in tropical savanna. Science Advances 3:1–8

Alexander S, Nelson CR, Aronson J, Lamb D, Cliquet A, Erwin KL, et al. (2011) Opportunities and challenges for ecological restoration within REDD+. Restoration Ecology 19:683–689

Allan E, Weisser W, Weigelt A, Roscher C, Fischer M, Hillebrand H (2011) More diverse plant communities have higher functioning over time due to turnover in complementary dominant species. Proceedings of the National Academy of Sciences 108:17034–17039

Aronson JC, Simberloff D, Ricciardi A, Goodwin N (2018) Restoration science does not need redefinition. Nature Ecology and Evolution 2:916

Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, Delire C, Mirin A (2007) Combined climate and carbon-cycle effects of large-scale deforestation. PNAS 104:6550–6555

Baumann M, Gasparri I, Piquer-Rodríguez M, Gavier Pizarro G, Griffiths P, Hostert P, Kuemmerle T (2017) Carbon emissions from agricultural expansion and intensification in the Chaco. Global Change Biology 23:1902–1916

Benayas JMR, Newton AC, Diaz A, Bullock JM (2009) Biodiversity and ecological restoration. Science 8:1121–1124

Bengtsson J, Bullock JM, Egoh B, Everson C, Everson T, O'Connor T, O'Farrell PJ, Smith HG, Lindborg R (2019) Grasslands—more important for ecosystem services than you might think. Ecosphere 10:e02582

Bolliger J, Bättig M, Gallati J, Kläy A, Stauffacher M, Kienast F (2011) Landscape multifunctionality: a powerful concept to identify effects of environmental change. Regional Environmental Change 11:203–206

Bond J (2012) Large parts of the world are brown or black: a different view on the "Green World" hypothesis. Journal of Vegetation Science 16:261–266

Bond WJ, Parr CL (2010) Beyond the forest edge: ecology, diversity and conservation of the grassy biomes. Biological Conservation 143:2395–2404

Bradshaw AD (2004) The role of nutrients and the importance of function in the assembly of ecosystems. Pages 325–340. In: Temperton VM, Hobbs R, Nuttle T, Halle S (eds) Assembly rules and restoration ecology. Island Press, Washington D.C.

Brown AE, Zhang L, McMahon TA, Western AW, Vertessy RA (2005) A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation. Journal of Hydrology 310:28–61

Bruelheide H, Nadrowski K, Assmann T, Bauhus J, Both S, Buscot F, et al. (2014) Designing forest biodiversity experiments: general considerations illustrated by a new large experiment in subtropical China. Methods in Ecology and Evolution 5:74–89

Buchmann T, Schumacher J, Ebeling A, Eisenhauer N, Fischer M, Gleixner G, et al. (2018) Connecting experimental biodiversity research to real-world grasslands. Perspectives in Plant Ecology, Evolution and Systematics 33:78–88

Bullock JM, Pywell RF, Burke MJW, Walker KJ (2001) Restoration of biodiversity enhances agricultural production. Ecology Letters 4:185–189

Bullock JM, Pywell RF, Walker KJ (2007) Long-term enhancement of agricultural production by restoration of biodiversity. Journal of Applied Ecology 44:6–12

Cao S, Tian T, Chen L, Dong X, Yu X, Wang G (2010) Damage caused to the environment by reforestation policies in arid and semi-arid areas of China. Ambio 39:279–283

Cao S, Chen L, Shankman D, Wang C, Wang X, Zhang H (2011) Excessive reliance on afforestation in China's arid and semi-arid regions: lessons in ecological restoration. Earth-Science Reviews 104:240–245

Carrington D (2017) The seven megatrends that could beat global warming: 'There is reason for hope'. https://www.theguardian.com/environment/2017/nov/08/seven-megatrends-that-could-beat-global-warming-climate-change (accessed 10 Jan 2019)

Carvalhais N, Forkel M, Khomik M, Bellarby J, Jung M, Migliavacca M, et al. (2014) Global covariation of carbon turnover times with climate in terrestrial ecosystems. Nature 514:213–217

Chazdon RL, Laestadius L (2016) Forest and landscape restoration: toward a shared vision and vocabulary. American Journal of Botany 103:1869–1871

Chazdon RL, Brancalion PHS, Lamb D, Laestadius L, Calmon M, Kumar C (2017) A policy-driven knowledge agenda for global forest and landscape restoration. Conservation Letters 10:125–132

Choi YD (2008) Ecological restoration for future sustainability. Ecology 15:53–64

Clewell A, Aronson J, Winterhalder K (2004) The SER International primer on ecological restoration. Ecological Restoration 2:206–207

Cord AF, Bartkowski B, Beckmann M, Dittrich A, Hermans-Neumann K, Kaim A, et al. (2017) Toward systematic analyses of ecosystem service

trade-offs and synergies: main concepts, methods and the road ahead. Ecosystem Services 28:264–272

Cortois R, Schröder-Georgi T, Weigelt A, van der Putten WH, De Deyn GB (2016) Plant–soil feedbacks: role of plant functional group and plant traits. Journal of Ecology 104:1608–1617

Cowie AL, Orr BJ, Castillo Sanchez VM, Chasek P, Crossman ND, Erlewein A, et al. (2018) Land in balance: the scientific conceptual framework for land degradation neutrality. Environmental Science and Policy 79:25–35

Crowther TW, Todd-Brown KEO, Rowe CW, Wieder WR, Carey JC, MacHmuller MB, et al. (2016) Quantifying global soil carbon losses in response to warming. Nature 540:104–108

Dass P, Houlto BZ, Wang Y, Warlind D (2018) Grasslands may be more reliable carbon sinks than forests in California. Environmental Research Letters 13:74027

Deng X, Li Z, Gibson J (2016) A review on trade-off analysis of ecosystem services for sustainable land-use management. Journal of Geographical Sciences 26:953–968

Dengler J, Janisova M, Török P, Wellstein C (2014) Agriculture, ecosystems and environment biodiversity of Palaearctic grasslands: a synthesis. Agriculture, Ecosystems and Environment 182:1–14

Díaz S, Pascual U, Stenseke M, Martín-López B, Watson RT, Molnár Z, et al. (2018) Assessing nature's contributions to people. Science 359:270–272

Dixon KW (2009) Pollination and restoration. Science 325:571–573

Duarte CM, Losada IJ, Hendriks IE, Mazarrasa I, Marbà N (2013) The role of coastal plant communities for climate change mitigation and adaptation. Nature Climate Change 3:961–968

Ekins P, Simon S, Deutsch L, Folke C, De Groot R (2003) A framework for the practical application of the concepts of critical natural capital and strong sustainability. Ecological Economics 44:165–185

Fichtner A, Härdtle W, Bruelheide H, Kunz M, Li Y, Von Oheimb G (2018) Neighborhood interactions drive overyielding in mixed-species tree communities. Nature Communications 9:1–8

Filoso S, Bezerra MO, Weiss KCB, Palmer MA (2017) Impacts of forest restoration on water yield: a systematic review. PLoS One 12:1–26

Fleischman FD (2014) Why do foresters plant trees? Testing theories of bureaucratic decision-making in central India. World Development 62:62–74

Forup ML, Henson KSE, Craze PG, Memmott J (2008) The restoration of ecological interactions: plant-pollinator networks on ancient and restored heathlands. Journal of Applied Ecology 45:742–752

Franz D, Acosta M, Altimir N, Arriga N, Arrouays D, Aubinet M, et al. (2018) Toward long-term standardized carbon and greenhouse gas observations for monitoring Europe's terrestrial ecosystems: a review. International Agrophysics 32:439–455

Fry GLA (2001) Multifunctional landscapes: towards transdisciplinary research. Landscape and Urban Planning 57:159–168

Gellie NJC, Breed MF, Mortimer PE, Harrison RD, Xu J, Lowe AJ (2018) Networked and embedded scientific experiments will improve restoration outcomes. Frontiers in Ecology and the Environment 16:288–294

Griggs D, Stafford-Smith M, Gaffney O, Rockström J, Öhman MC, Shyamsundar P, Steffen W, Glaser G, Kanie N, Noble I (2013) Sustainable development goals for people and planet. Nature 495:305–307

Griscom BW, Adams J, Ellis PW, Houghton RA, Lomax G, Miteva DA, et al. (2017) Natural climate solutions. Proceedings of the National Academy of Sciences 114:11645–11650

Habel JC, Dengler J, Janišová M, Török P, Wellstein C, Wiezik M (2013) European grassland ecosystems: threatened hotspots of biodiversity. Biodiversity and Conservation 22:2131–2138

Harris JA, Hobbs RJ, Higgs ES, Aronson J (2006) Ecological restoration and global climate change. Restoration Ecology 14:170–176

Hewitt N, Klenk N, Smith AL, Bazely DR, Yan N, Wood S, MacLellan JI, Lipsig-Mumme C, Henriques I (2011) Taking stock of the assisted migration debate. Biological Conservation 144:2560–2572

Higgs ES, Harris JA, Heger T, Hobbs RJ, Murphy SD, Suding KN (2018) Keep ecological restoration open and flexible. Nature Ecology and Evolution 2:580

Hobbs RJ (2016) Degraded or just different? Perceptions and value judgements in restoration decisions. Restoration Ecology 24:153–158

Hoekstra JM, Boucher TM, Ricketts TH, Roberts C (2005) Confronting a biome crisis: global disparities of habitat loss and protection. Ecology Letters 8:23–29

Honda EA, Durigan G (2016) Woody encroachment and its consequences on hydrological processes in the savannah. Philosophical Transactions of the Royal Society B: Biological Sciences 371:1–9

Huang Y, Chen Y, Castro-Izaguirre N, Baruffol M, Brezzi M, Lang A, et al. (2018) Supplementary material for: impacts of species richness on productivity in a large-scale subtropical forest experiment. Science 362:80–83

IPBES (2018) The IPBES assessment report on land degradation and restoration. In: Montanarella L, Scholes R, Brainich A (eds) Secretariat of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services, Bonn, Germany

Isbell F, Calcagno V, Hector A, Connolly J, Harpole WS, Reich PB, et al. (2011) High plant diversity is needed to maintain ecosystem services. Nature 477:199–202

Isbell F, Craven D, Connolly J, Loreau M, Schmid B, Beierkuhnlein C, et al. (2015) Biodiversity increases the resistance of ecosystem productivity to climate extremes. Nature 526:574–577

Jackson RB, Jobbágy EG, Avissar R, Roy SB, Barrett DJ, Cook CW, et al. (2005) Atmospheric science: trading water for carbon with biological carbon sequestration. Science 310:1944–1947

Jacobs K, Garfin G, Lenart M (2005) More than just talk: connecting science and decision making. Environment: Science and Policy for Sustainable Development 47:6–21

Jaeschke A, Bittner T, Jentsch A, Beierkuhnlein C (2014) The last decade in ecological climate change impact research: where are we now. Naturwissenschaften 101:1–9

Jobbágy EG, Jackson RB (2000) The vertical distribution of soil organic carbon and its relation to climate and vegetation. Ecological Applications 10:423–436

Jonson J (2010) Ecological restoration of cleared agricultural land in Gondwana Link: lifting the bar at "Peniup". Ecological Management and Restoration 11:16–26

Lange M, Eisenhauer N, Sierra CA, Bessler H, Engels C, Griffiths RI, et al. (2015) Plant diversity increases soil microbial activity and soil carbon storage. Nature Communications 6:1–8

Levis C, Costa FRC, Bongers F, Peña-Claros M, Clement CR, Junqueira AB, et al. (2017) Persistent effects of pre-Columbian plant domestication on Amazonian forest composition. Science 355:925–931

Li Y, Cao Z, Long H, Liu Y, Li W (2017) Dynamic analysis of ecological environment combined with land cover and NDVI changes and implications for sustainable urban–rural development: the case of Mu Us Sandy Land, China. Journal of Cleaner Production 142:697–715

Loescher HW, Kelly E, Lea R (2017) National ecological observatory network: beginnings, programmatic and scientific challenges, and ecological forecasting. Pages 27–51. In: Chabbi Abad, Loescher Henry W (eds) Terrestrial ecosystem research infrastructures: challenges and opportunities. CRC Press, Boca Raton, Florida

Lovell ST, Johnston DM (2009) Creating multifunctional landscapes: how can the field of ecology inform the design of the landscape? Frontiers in Ecology and the Environment 7:212–220

Luyssaert S, Marie G, Valade A, Chen YY, Njakou Djomo S, Ryder J, et al. (2018) Trade-offs in using European forests to meet climate objectives. Nature 562:259–262

Mansourian S (2017) Governance and forest landscape restoration: a framework to support decision-making. Journal for Nature Conservation 37:21–30

Mansourian S, Stanturf JA, Derkyi MAA, Engel VL (2017) Forest landscape restoration: increasing the positive impacts of forest restoration or simply the area under tree cover? Restoration Ecology 25:178–183

Marquard E, Weigelt A, Temperton VM, Roscher C, Schumacher J, Buchmann N, Fischer M, Weisser WW, Schmid B (2009) Plant species richness and functional composition drive overyielding in a six-year grassland experiment. Ecology 90:3290–3302

Matthews RJB, Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, et al. (2018) Global warming of 1.5°C. An IPCC special report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. IPCC, Geneva, Switzerland

Mcdonald T, Gann GD, Jonson J, Dixon KW (2016) International standards for the practice of ecological restoration—including principles and key concepts. Society for Ecological Restoration, Washington D.C.

McLeod E, Chmura GL, Bouillon S, Salm R, Björk M, Duarte CM, Lovelock CE, Schlesinger WH, Silliman BR (2011) A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO2. Frontiers in Ecology and the Environment 9:552–560

McNie EC (2007) Reconciling the supply of scientific information with user demands: an analysis of the problem and review of the literature. Environmental Science & Policy 10:17–38

Meyer ST, Ebeling A, Eisenhauer N, Hertzog L, Hillebrand H, Milcu A, et al. (2016) Effects of biodiversity strengthen over time as ecosystem functioning declines at low and increases at high biodiversity. Ecosphere 7:e01619

Meyer ST, Ptacnik R, Hillebrand H, Bessler H, Buchmann N, Ebeling A, et al. (2018) Biodiversity-multifunctionality relationships depend on identity and number of measured functions. Nature Ecology and Evolution 2:44–49

Meyer-Grünefeldt M, Calvo L, Marcos E, Von Oheimb G, Härdtle W (2015) Impacts of drought and nitrogen addition on Calluna heathlands differ with plant life-history stage. Journal of Ecology 103:1141–1152

Montoya D, Rogers L, Memmott J (2012) Emerging perspectives in the restoration of biodiversity-based ecosystem services. Trends in Ecology and Evolution 27:666–672

Moreira da Silva AP, Schweizer D, Rodrigues Marques H, Cordeiro Teixeira AM, Nascente dos Santos TVM, Sambuichi RHR, Badari CG, Gaudare U, Brancalion PHS (2017) Can current native tree seedling production and infrastructure meet an increasing forest restoration demand in Brazil? Restoration Ecology 25:509–515

Noojipady P, Morton CD, Macedo NM, Victoria CD, Huang C, Gibbs KH, Bolfe LE (2017) Forest carbon emissions from cropland expansion in the Brazilian Cerrado biome. Environmental Research Letters 12:025004

O'Farrell PJ, Anderson PML (2010) Sustainable multifunctional landscapes: a review to implementation. Current Opinion in Environmental Sustainability 2:59–65

Overbeck GE, Vélez-Martin E, Scarano FR, Lewinsohn TM, Fonseca CR, Meyer ST, et al. (2015) Conservation in Brazil needs to include non-forest ecosystems. Diversity and Distributions 21:1455–1460

Pan Y, Birdsey RA, Fang J, Houghton R, Kauppi PE, Kurz WA, et al. (2011) A large and persistent carbon sink in the world's forests. Science 333:988–993

Pausas JG, Bond WJ (2018) Humboldt and the reinvention of nature. Journal of Ecology 1:031–1,037

Perring MP, Standish RJ, Price JN, Craig MD, Erickson TE, Ruthrof KX, Whiteley AS, Valentine LE, Hobbs RJ (2015) Advances in restoration ecology: rising to the challenges of the coming decades. Ecosphere 6:1–25

Perring MP, Erickson TE, Brancalion PHS (2018) Rocketing restoration: enabling the upscaling of ecological restoration in the Anthropocene. Restoration Ecology 26:1017–1023

Phelps J, Friess DA, Webb EL (2012) Win-win REDD+ approaches belie carbon-biodiversity trade-offs. Biological Conservation 154:53–60

Pinto SR, Melo F, Tabarelli M, Padovesi A, Mesquita CA, de Mattos Scaramuzza CA, et al. (2014) Governing and delivering a biome-wide restoration initiative: the case of Atlantic Forest Restoration Pact in Brazil. Forests 5:2212–2229

Poorter L, van der Sande MT, Thompson J, Arets EJMM, Alarcón A, Álvarez-Sánchez J, et al. (2015) Diversity enhances carbon storage in tropical forests. Global Ecology and Biogeography 24:1314–1328

Popkin G (2019) The forest question. Nature 565:280–282

Posner SM, Cvitanovic C (2019) Evaluating the impacts of boundary-spanning activities at the interface of environmental science and policy: a review of progress and future research needs. Environmental Science & Policy 92:141–151

Potvin C, Gotelli NJ (2008) Biodiversity enhances individual performance but does not affect survivorship in tropical trees. Ecology Letters 11:217–223

Ravenek JM, Bessler H, Engels C, Scherer-Lorenzen M, Gessler A, Gockele A, et al. (2014) Long-term study of root biomass in a biodiversity experiment reveals shifts in diversity effects over time. Oikos 123:1528–1536

Reisser M, Purves RS, Schmidt MWI, Abiven S (2016) Pyrogenic carbon in soils: a literature-based inventory and a global estimation of its content in soil organic carbon and stocks. Frontiers in Earth Science 4:1–14

Ribeiro MC, Metzger JP, Martensen AC, Ponzoni FJ, Hirota MM (2009) The Brazilian Atlantic Forest: how much is left, and how is the remaining forest distributed? Implications for conservation. Biological Conservation 142:1141–1153

Roberts L, Stone R, Sugden A (2009) The rise of restoration ecology. Science 325:555–555

Roscher C, Schumacher J, Baade J, Wilke WW, Gleixner G, Weisser WW, Schmid B, Schulze ED (2004) The role of biodiversity for element cycling and trophic interactions: an experimental approach in a grassland community. Basic and Applied Ecology 5:107–121

Roscher C, Thein S, Weigelt A, Temperton VM, Buchmann N, Schulze ED (2011) N_2 fixation and performance of 12 legume species in a 6-year grassland biodiversity experiment. Plant and Soil 341:333–348

Scherber C, Eisenhauer N, Weisser WW, Schmid B, Voigt W, Fischer M, et al. (2010) Bottom-up effects of plant diversity on multitrophic interactions in a biodiversity experiment. Nature 468:553–556

Schulze ED, Bouriaud O, Weber U, Roscher C, Hessenmoeller D, Kroiher F, Schall P (2018) Management breaks the natural productivity-biodiversity relationship in forests and grassland: an opinion. Forest Ecosystems 5:1–8

Scott CE, Monks SA, Spracklen DV, Arnold SR, Forster PM, Rap A, et al. (2018) Impact on short-lived climate forcers increases projected warming due to deforestation. Nature Communications 9:1–9

Searchinger TD, Estes L, Thornton PK, Beringer T, Notenbaert A, Rubenstein D, Heimlich R, Licker R, Herrero M (2015) High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. Nature Climate Change 5:481–486

Seddon N, Turner B, Berry P, Chausson A, Girardin CAJ (2019) Grounding nature-based climate solutions in sound biodiversity science. Nature Climate Change 9:84–87

Steffen W, Richardson K, Rockström J, Cornell SE, Fetzer I, Bennett EM, et al. (2015) Planetary boundaries: guiding human development on a changing planet. Science 347:1–11

Suding KN (2011) Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Annual Review of Ecology, Evolution, and Systematics 42:465–487

Suding K, Higgs E, Palmer M, Callicott JB, Anderson CB, Baker M, et al. (2015) Committing to ecological restoration. Science 348:638–640

Temperton V, Hobbs R, Nuttle T, Halle S (2004) Assembly rules and restoration ecology: bridging the gap between theory and practice. Island Press, Washington D.C.

Thakur MP, Milcu A, Manning P, Niklaus PA, Roscher C, Power S, et al. (2015) Plant diversity drives soil microbial biomass carbon in grasslands irrespective of global environmental change factors. Global Change Biology 21:4076–4085

Tittensor DP, Walpole M, Hill SLL, Boyce DG, Britten GL, Burgess ND, et al. (2014) A mid-term analysis of progress toward international biodiversity targets. Science 346:241–244

Tong C, Le Duc M, Ghorbani J, Marrs R (2006) Linking restoration to the wider landscape: a study of a bracken control experiment within a upland moorland landscape mosaic in the Peak District, UK. Landscape and Urban Planning 78:115–134

Uchida E, Xu J, Rozelle S (2015) Grain for green: cost-effectiveness and sustainability of China's conservation set-aside program. Land Economics 81:247–264

UNCCD (2013) Report of the Conference of the Parties on its eleventh session. United Nations Office, Geneva, Switzerland

Unger N (2014) Human land-use-driven reduction of forest volatiles cools global climate. Nature Climate Change 4:907–910

Veldman JW, Overbeck GE, Negreiros D, Mahy G, Le Stradic S, Fernandes GW, et al. (2015a) Where tree planting and forest expansion are bad for biodiversity and ecosystem services. BioScience 65:1011–1018

Veldman JW, Buisson E, Durigan G, Fernandes GW, Le Stradic S, Mahy G, et al. (2015b) Toward an old-growth concept for grasslands, savannas, and woodlands. Frontiers in Ecology and the Environment 13:154–162

Veldman JW, Silveira FAO, Fleischman FD, Ascarrunz NL, Durigan G (2017) Grassy biomes: an inconvenient reality for large-scale forest restoration? A comment on the essay by Chazdon and Laestadius. American Journal of Botany 104:1–3

Walker LR, Walker M, Hobbs Richard (2007) Linking restoration and ecological succession. Springer, Berlin Heidelberg, Germany

Weidlich EWA, von Gillhaussen P, Delory BM, Blossfeld S, Poorter H, Temperton VM (2017a) The importance of being first: exploring priority and diversity effects in a grassland field experiment. Frontiers in Plant Science 7:2008

Weidlich EWA, von Gillhaussen P, Max JFJ, Delory BM, Jablonowski ND, Rascher U, Temperton VM (2017b) Priority effects caused by plant order of arrival affect below-ground productivity. Journal of Ecology 106: 774–780

Weisser WW, Roscher C, Meyer ST, Ebeling A, Luo G, Allan E, et al. (2017) Biodiversity effects on ecosystem functioning in a 15-year grassland experiment: patterns, mechanisms, and open questions. Basic and Applied Ecology 23:1–73

Wiedinmeyer C, Hurteau MD (2010) Prescribed fire as a means of reducing forest carbon emissions in the western United States. Evironmental Science Technology 44:1926–1932

Wolosin M, Breitfeller J, Schaap B (2016) The geography of REDD+: deforestation, emissions, and the targeting of forest conservation finance. Forest Trends' Forest Policy, Trade, and Finance program report. Forest Trends, Washington D.C.

Yang Y, Furey G, Lehman C, Tilman D (2019) Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nature Communications 10:1–7

Zavaleta ES, Zavaleta ES, Shaw MR, Shaw MR, Chiariello NR, Chiariello NR, et al. (2003) Additive effects of simulated climate changes, elevated CO2, and nitrogen deposition on grassland diversity. PNAS 100: 7650–7654

Zemp DC, Schleussner CF, Barbosa HMJ, Van Der Ent RJ, Donges JF, Heinke J, Sampaio G, Rammig A (2014) On the importance of cascading moisture recycling in South America. Atmospheric Chemistry and Physics 14:13337–13359

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