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POLICY ARTICLE

Prioritize grassland restoration to bend the curve of biodiversity loss

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In times of unprecedented climate change, ecological restoration efforts have a strong focus on forests for the purpose of carbon sequestration. Grasslands, in contrast, remain relatively neglected in global restoration policies. Concurrently, we are in the midst of a biodiversity crisis—it is estimated that 1 million species are globally threatened with extinction. Here, we present analyses from central Europe and southern Brazil that show that the majority of our endangered plant species are in fact found in open ecosystems. Using Germany as an example, we show that we could reduce plant extinction risk by up to 82% if we restore open, grassy ecosystems. This also holds true for southern Brazil, where grassland species constitute the single largest share of endangered species, but where grassy ecosystems continue to be systematically neglected by restoration policies. We further expand on our biodiversity argument to include the role that grassland restoration can play in mitigating climate change. We posit that ramping up grassland restoration efforts may not only be our best bet to bend the curve of biodiversity loss, but it will also make a critical contribution to the resilience of ecosystems in the dynamic decades to come. It is time for grassland restoration to receive higher priority in global restoration efforts and policy.

Key words: biodiversity crisis, ecosystem resilience, extinction risk, forest bias, natural climate solutions, restoration policy

Conceptual Implications

- Global restoration policy has a strong focus on mitigating climate change, often overshadowing efforts to restore biodiversity itself. Policymakers tend to view forests as the epitome of biodiversity with significant carbon sequestration potential, placing forest restoration high on the policy agenda.
- We combine data from Europe and Brazil that suggest grassy ecosystems, not forests, comprise higher levels of threatened plant biodiversity. Hence, in many parts of the world, our best chance of bending the biodiversity curve lies not in restoring forests, but rather grasslands.
- Given recent evidence on the ability of grasslands to also mitigate climate change, restoring grasslands can address both the biodiversity and climate crises and deserve greater attention in the global policy arena for restoration.

Forest Restoration and the Biodiversity Crisis

We are currently facing the twin global pressures of anthropogenic climate change and biodiversity loss. Both political and scientific actions aimed at tackling these issues focus predominantly on carbon sequestration, and consequently, forest restoration is proposed as the prevailing nature-based solution to the climate and biodiversity crisis (e.g. Lewis et al. 2019; di Sacco et al. 2021). For example, the Bonn Challenge, launched in 2011, aims to restore 350 million hectares of forest worldwide by 2030 (bonnchallenge.org); the World Economic Forum 2021 has launched 1t.org, a global tree planting program to support the UN Decade for Ecosystem Restoration 2021–2030 (decadeonrestoration.org); the EU Forest Strategy aims to plant three billion trees by 2030 (environment.ec.europa.eu/strategy/forest-strategy_en); and at a more national level, Germany has pledged four billion euros from 2023 for the Climate Action Program, which includes creating 10,000 additional hectares of forest annually by 2030 (bmuv.de/download/aktionsprogramm-natuerlicher-klimaschutz). This policy momentum of focusing on restoring forests tends to overshadow complementary restoration needs, such as grassland, peatland, or savanna restoration.

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There are also concerns over how compatible "restoration" for carbon sequestration is with restoration for biodiversity (Seddon et al. 2019). Here, we provide novel analyses that demonstrate why we need to restore grasslands if we are to "bend the curve of biodiversity loss" (Mace et al. 2018). We use Germany and southern Brazil as example regions with both forests and grasslands and a policy context representative of central Europe and parts of the southern hemisphere where, despite profound losses of biodiverse grasslands, forests dominate the restoration agenda (Overbeck et al. 2007; Temperton et al. 2019; Silveira et al. 2020; Eufemia et al. 2023).

Historical Models of Wilderness Disfavor Grasslands in Restoration Policy

A major reason why grasslands are often overlooked, both politically and ecologically, is the long-standing debate over the state of natural vegetation in central Europe. Conventional wisdom was that postglacial succession naturally led to closed-canopy forest covering the vast majority of central Europe (Vera 2000). Prevailing ecologists of the 19th and early 20th centuries observed abandoned land naturally returning to forest cover and assumed this to be the natural end point of vegetation succession (Cotta 1865; Landolt 1895; Tansley 1911; Clements 1916). The concept that many nonforest ecosystems must be degraded remains prevalent in both the scientific and policy literature today (Veldman et al. 2015; Buisson et al. 2022). This view is, however, partially contradicted by pre-agricultural pollen records indicating high proportions of light-demanding species (Vera 2000). Furthermore, there is also increasing evidence to suggest that natural disturbance regimes, such as relatively high densities of ungulates, may have played a large role in creating heterogeneous, mosaic-like vegetation structures, comprising both forest and grassland sites across Europe, thereby able to sustain a high diversity of light-demanding species (Vera 2000; Svenning 2002; Bradshaw et al. 2003; Feurdean et al. 2018). These observations are similarly echoed in South American and African landscapes that are currently considered deforested but may in fact represent a natural forest-savannah landscape where fires and/or herbivores have long maintained biodiversity (Pausas & Bond 2019; Buisson et al. 2022). Additionally, so-called "pristine" environments found by white European settlers in North America or Australia were often landscapes that had been extensively managed by indigenous people for millennia (Fuhlendorf et al. 2009; Lewis & Maslin 2015). Local tribes were often forcibly removed in order to create conserved areas, based in part on the dichotomy between humans and nature (Dowie 2011). This worldview continues to have important repercussions on how we value and manage land for biodiversity, as well as which habitats we focus on. The historically dominant mental model of naturally closed forested landscapes (Vera 2000; Pausas & Bond 2019) has led decision-makers to view forests, not only as pivotal natural solutions for climate change mitigation but also as the epitome of biodiversity, "naturalness" or "wilderness," thus placing them at the forefront of restoration efforts.

Restoring for Biodiversity Requires Understanding Which Species Are Currently Lost

The IPBES global assessment estimates that 1 million species are at risk of extinction (IPBES 2019). Against the backdrop of current biodiversity loss, it is critical to prioritize restoration efforts on endangered species and their respective habitats. In Germany, for example, approximately 31% of the country's vascular plant species, roughly 1,400 taxa, are currently listed on the Red List as endangered (Metzing et al. 2018). We used the 1998 and 2018 Red Lists for Germany (rote-liste-zentrum.de), and Ellenberg indicator values to quantify how species are represented on these lists relative to their niches and to evaluate change over time. Given that grassland species require high amounts of light (Ellenberg et al. 1991), we focus on species light values (EIV-L). We also compare the threat status for light demand to the threat status for nutrient demand (EIV-N), given that anthropogenic pressures involving eutrophication are often identified as primary drivers of species decline (Bobbink et al. 2010; Metzing et al. 2018). We find that species in the high light (EIV-L 7–9) and low nutrient (EIV-N 1–3) ranges are disproportionately at risk, even after accounting for the relatively high proportion of these species in Germany (Fig. 1A). While the average threat status across all species is 31%, the proportion of threatened species with high light and low nutrient demands is much higher. In fact, nearly every second species requiring full light (EIV-L 9 = 51%; EIV-L 8 = 41%) or soils poor in nutrients (EIV-N 1 = 51%; EIV-N 2 = 51%) are endangered. In comparison, species with low light and high nutrient demands are far less likely to be threatened (EIV-L 1 = 0%, EIV-L 2 = 19%, EIV-N 8 = 12%, EIV-N 9 = 31%; Fig. 1A). Furthermore, light-demanding species are disproportionately more likely to become threatened over time (Fig. 1B). The overall threat status of the German flora increased by 6.2 percentage points from 1998 to 2018. While the threat status of low- to medium-light species (EIV-L < 7) increased by an average of 1.3 percentage points, the threat status of high-light plants (EIV-L ≥ 7) increased by an average of 9 percentage points. We did not, however, observe this trend for low EIV-N species, as might be expected given the ongoing, widespread negative effects of eutrophication (Fig. 1B, right). Furthermore, these percentages apply to the total German flora; if we instead confine this analysis to the pool of endangered species only, we find that light-demanding species account for a striking 82% of all endangered species on the German Red List (Fig. 1C). This is well above the proportion of low-N plants (61%).

Most Endangered Species May Benefit From Grassland Rather Than Forest Restoration

Our analysis shows that the vast majority (82%) of endangered species in Germany require high light availability, indicating that four out of five endangered species are unlikely to benefit from forest restoration (that typically results in shaded habitats). In contrast, species from shaded habitats make up merely 1% of endangered species. Given the high threat status of light-demanding species, restoration efforts that aim to protect plant biodiversity may be well-advised to focus attention on habitats that provide

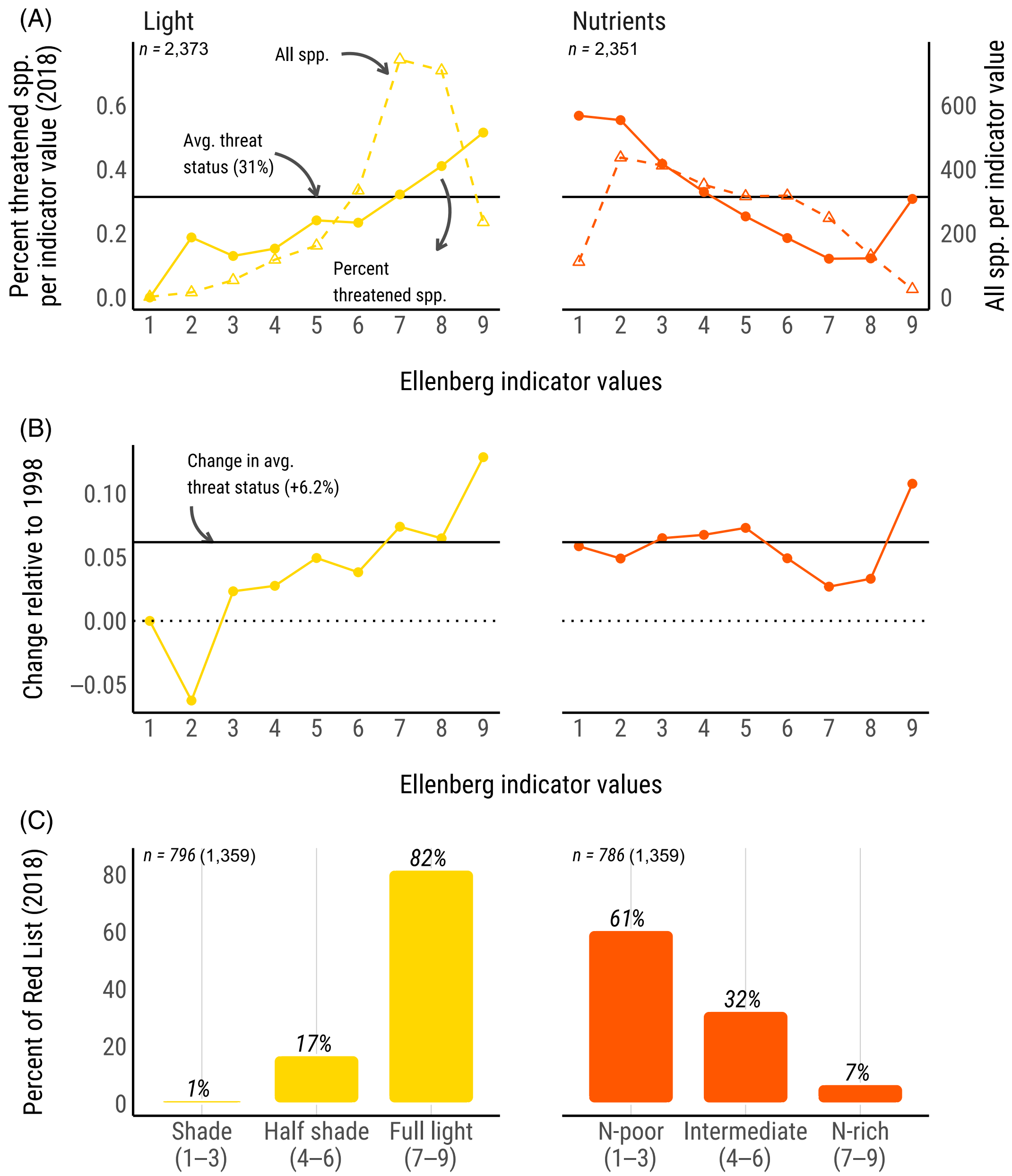


Figure 1. The extinction risk for light-demanding species is disproportionately high and has increased at an above-average rate over the last 20 years, with 82% of all endangered species on the 2018 Red List of Germany being light-demanding species. By comparison, the figure for nutrient-efficient species, which are also disproportionately endangered but whose extinction risk has not increased at an above-average rate, is 61%. (A) Ellenberg indicator value spectra of the vascular plants of Germany for light (EIV-L; 1–9 stands for species that have their niche optimum in full shade or full light, respectively) and nutrients (EIV-N; 1–9: nutrient-efficient to nitrophilous species, respectively). Dashed line shows the number of species per indicator value in Germany (2,373 and 2,351 species have EIV-L and EIV-N values, respectively). Solid line shows the percentage of endangered species (i.e. species with Red List status 0, 1, 2, 3, or G) per indicator value (e.g. there are 162 assessed species with EIV-L = 5, of which 24% are endangered). Black solid line at 0.31 shows the 2018 average threat status of all species. (B) Changes in the percentage of endangered species per indicator value compared to the 1998 Red List. Black solid line at 0.062 shows the overall increase in threat status for all species. Dotted line at zero indicates no change. (C) Percentage of endangered species in the 2018 Red List in relation to their light and nutrient requirements. A total of 1,359 taxa are listed as endangered. EIVs for L and N were available for 796 and 786 endangered species, respectively. German Red Lists were downloaded from, Ellenberg indicator values were retrieved from sci.muni.cz/botany/juice/ELLENB.TXT.

this requirement, namely open, grassy ecosystems (Ellenberg et al. 1991). In order to determine the threat trajectory of different growth forms, we used data from the German synthesis project sMon (Eichenberg et al. 2021). These data show that woody species, that is, shrubs and trees, have increased their range by 32%, on average, since 1960, a markedly positive average population trend in Germany (raw data: Fig. 2A; estimated means: Fig. 2B). This finding is echoed in a recent time-series meta-analysis for Germany which finds that forest species are increasing (Jandt et al. 2022). While we are not able to empirically determine

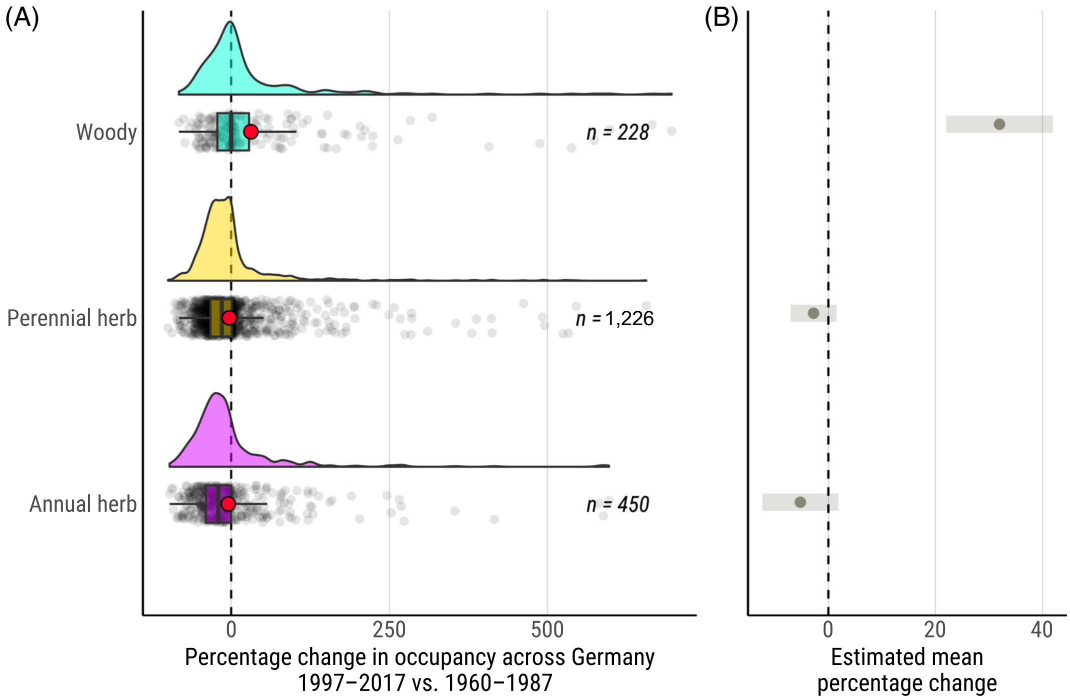


Figure 2. Woody species have increased by an average of 32% across Germany in recent decades. (A) Density, boxplot, and jittered data points for species occupancy change (expressed as percentage) for the major life forms of vascular plants ("herbs" here include grasses and sedges). Species occupancy refers to the number of occupied 5 km^2 grid cells in Germany, percentage change in occupancy is calculated by $(t1 - t0)/t0 \times 100$, where $t0$ and $t1$ are the occupancy at the starting (1960–1987) and end period (1997–2017) of the survey. Data are from Eichenberg et al. (2021). Data on species occupancy trends were available for 228 woody species, 1,226 perennial herbs, and 450 annual herbs. Boxplots bound the interquartile range (IQR) divided by the median and whiskers extend up to a maximum of 1.5 × IQR beyond the box. Red dots indicate the mean. (B) Estimated mean percentage change in species occupancy together with 95% credible intervals. Vertical dotted line at zero presents no change.

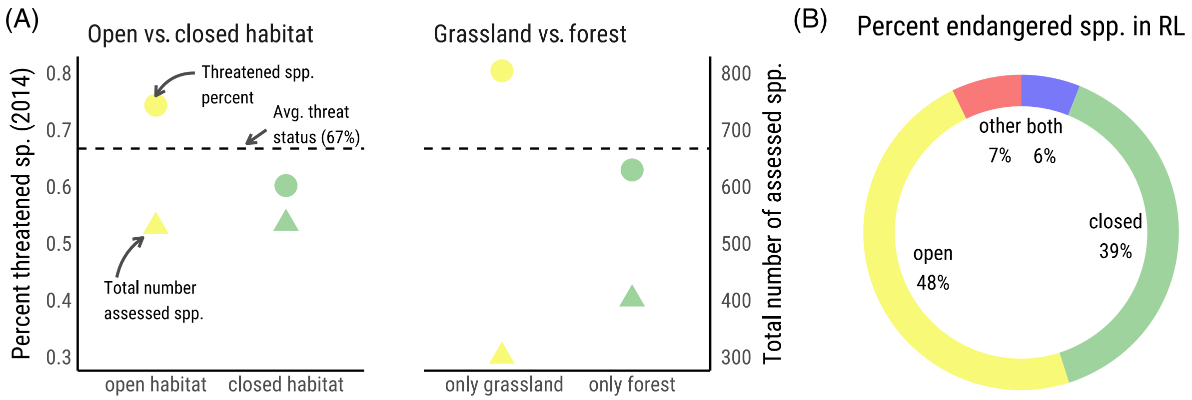
a causal relationship between the decline in light-demanding and the increase in woody species here, we suggest it is plausible that they are at least partially related in many places. Widespread declines in historical land use contribute to the loss of open habitats and their biodiversity (Bieling et al. 2013; Wang et al. 2023), such as when semi-natural grasslands with traditional management (e.g. pastoralism) are afforested (Wang et al. 2023) or abandoned and woody species increase during succession (Diekmann et al. 2019; Staude et al. 2022). We accompany this Eurocentric analysis with data, albeit less comprehensive, from southern Brazil and find that most endangered species here are also grassland species (Box 1). Despite the disproportionate threat to grassland species, tree planting is often considered synonymous with restoration, regardless of the ecosystem being restored, and often at the expense of grassland in Brazil. We do not mean to suggest that forests cannot contribute to biodiversity restoration—they can, especially in regions where forests are declining, but we stress that grasslands must be valued as hotspots of *threatened* biodiversity and their restoration accelerated if we are to successfully bend the curve of biodiversity loss.

Grassland Restoration Can Address Both the Biodiversity and Climate Crises

These data suggest that restoring grasslands may represent our most efficient approach to bend the curve of biodiversity loss, but we also suggest they can contribute significantly to the mitigation of and adaptation to climate change. While grasslands cannot accumulate biomass aboveground to the same extent as forests and therefore (initially) sequester less carbon aboveground, their carbon stores are overall more resilient to increasing drought and fire events due to their ability to sequester large amounts of carbon belowground and their long history of being adapted to disturbance such as fires, droughts, and grazing (Dass et al. 2018). Thus, while forests may transition from C sinks to C sources in some regions already this century (McDowell & Allen 2015), grasslands may be less susceptible to climate extremes and hence more reliable in maintaining C sinks over longer periods of time (Vicente-Serrano et al. 2013; Dass et al. 2018). Moreover, grasslands and forests differ decisively in their albedo (Rohatyn et al. 2022). The lower albedo of forests can lead to warming, which can offset some of the positive effects of carbon sequestration from afforestation (Rohatyn et al. 2022). Conversely, grasslands have higher albedo *and* are a key soil carbon sink, storing about one-third of the world's terrestrial carbon (White et al. 2000). The full potential for grasslands as carbon sinks requires more attention and remains unrealized at present. For example, it is estimated that 80% of Europe's grasslands are below saturation of carbon storage, highlighting vast opportunities for more sequestration (Bai & Cotrufo 2022). Management can also have a decisive impact on the carbon sequestration potential of grasslands, with

Box 1 A case study from southern Brazil: Although extinction risk for grassland species outnumbers that of forest species, restoration predominantly focuses on forests

Similar endangerment patterns to Germany can also be found in Rio Grande do Sul, Brazil. The southernmost state in Brazil includes both forest (part of the Atlantic Forest biodiversity hotspot) and subtropical grassland and provides an excellent opportunity for comparing endangerment status in open and closed habitats. Using the 2014 Red List (RL) for the state (RS 2014), we find that open habitat or only grassland species are disproportionately at risk of extinction. This list assessed 1,237 plant species, 67% of which are classified as endangered (categories EX, RE, VU, CR, EN; dashed line in A). Slightly more closed habitat/only forest species were assessed than open habitat/only grassland species (triangles in A). Yet the proportion of assessed species that are endangered was considerably higher for grassland than forest species (74 and 80% vs. 60 and 63%, respectively, for open habitat/only grassland vs. closed habitat/only forest, circles in A). Examining only the endangered species on the 2014 RL, we find that grassland species make up the single largest share: 48% of endangered species are open habitat species, compared to 39% closed habitat species (B). This disproportionate endangerment of grassland species in this region of Brazil is remarkable for two reasons: (1) the Brazilian Atlantic Forest is one of the most threatened biomes in the world, and (2) when one thinks of the flora of Brazil, one does not usually think of biodiverse grasslands or that they are potentially at high risk. This biome-bias reflects the continued neglect of grassland ecosystems in Brazil, despite researchers finding that grassy biomes have the highest conservation risk index in Brazil (Overbeck et al. 2015). Given the lack of awareness of the biodiversity of these systems, nonexisting restoration policies, major botanical data gaps, and a research bias toward forest, these systems are undergoing and will likely continue to undergo rapid conversion (Overbeck et al. 2022). In the last 20 years, approximately 50% of native grassy ecosystems in southern Brazil have been converted not only to soybean and corn cultivation but also to "restored" forested areas. State environmental agencies often require tree planting as a restoration measure to compensate for environmental damage, and tree planting is considered synonymous with restoration, regardless of the ecosystem to be restored. This case study highlights, however, that grasslands can account for the majority of endangered species and accordingly, if we want to restore biodiversity, we must conserve and restore grasslands.



improved grazing management and biodiversity restoration providing low-cost and high-carbon-gain options for natural climate solutions that may be complementary to forests in the long run (Yang et al. 2019; Pastore et al. 2021; Bai & Cotrufo 2022). Given the additional potential for both carbon sequestration and climate cooling (Temperton et al. 2019), grassland restoration deserves much more momentum in global restoration efforts and policy as natural climate solution, adaptation agent, and biodiversity provider.

Time for Global Restoration Policy to Focus on Grasslands

In sum, there is a clear biodiversity-centered argument for grassland restoration: Grassland restoration could contribute substantially to reducing extinction risk for plants—far more than forest restoration in some places, according to our analysis. Alongside biodiversity benefits, grassland restoration can also provide a variety of ecosystem services essential to tackling climate change. As the frequency of fires and drought events increase, grassland soils may present more reliant carbon reservoirs than forests, since they are innately adapted to disturbance and have longer carbon turnover times than forests (Carvalhais et al. 2014). Since carbon sequestration by grasslands increases with biodiversity (Steinbeiss et al. 2008; Yang et al. 2019), restoring grasslands is a holistic effort to tackling both the biodiversity and climate crisis. Finally, since light-demanding species are often also well-adapted to drier and more extreme weather events (both trends of global climate change), and diversity in grasslands begets stability (Tilman & Downing 1994), sustaining and restoring diverse grasslands can make a critical contribution to the resilience of our ecosystems in the dynamic decades to come. Rather than viewing grasslands as extra land for forest restoration, it is time for policy to view our grasslands as a critical asset for sustaining a biodiverse, resilient, and healthy planet.

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LITERATURE CITED

Bai Y, Cotrufo MF (2022) Grassland soil carbon sequestration: current understanding, challenges, and solutions. Science 377:603–608. https://doi.org/10.1126/science.abo2380

Bieling C, Plieninger T, Schaich H (2013) Patterns and causes of land change: empirical results and conceptual considerations derived from a case study in the Swabian Alb, Germany. Land Use Policy 35:192–203. https://doi.org/10.1016/j.landusepol.2013.05.012

Bobbink R, Hicks K, Galloway J, Spranger T, Alkemade R, Ashmore M, et al. (2010) Global assessment of nitrogen deposition effects on terrestrial plant diversity: a synthesis. Ecological Applications 20:30–59. https://doi.org/10.1890/08-1140.1

Bradshaw RHW, Hannon GE, Lister AM (2003) A long-term perspective on ungulate–vegetation interactions. Forest Ecology and Management 181:267–280. https://doi.org/10.1016/S0378-1127(03)00138-5

Buisson E, Archibald S, Fidelis A, Suding KN (2022) Ancient grasslands guide ambitious goals in grassland restoration. Science 377:594–598. https://doi.org/10.1126/science.abo4605

Carvalhais N, Forkel M, Khomik M, Bellarby J, Jung M, Migliavacca M, Saatchi S, Santoro M, Thurner M, Weber U (2014) Global covariation of carbon turnover times with climate in terrestrial ecosystems. Nature 514:213–217. https://doi.org/10.1038/nature13731

Clements FE (1916) Plant succession: an analysis of the development of vegetation. Carnegie Institution of Washington, Washington D.C. https://doi.org/10.5962/bhl.title.56234

Cotta H (1865) Anweisung zum Waldbau (Neunte, neubearbeitete Auflage). Arnoldische Buchhandlung, Leipzig

Dass P, Houlton BZ, Wang Y, Warlind D (2018) Grasslands may be more reliable carbon sinks than forests in California. Environmental Research Letters 13:074027. https://doi.org/10.1088/1748-9326/aacb39

Diekmann M, Andres C, Becker T, Bennie J, Blüml V, Bullock JM, et al. (2019) Patterns of long-term vegetation change vary between different types of semi-natural grasslands in Western and Central Europe. Journal of Vegetation Science 30:187–202. https://doi.org/10.1111/jvs.12727

Dowie M (2011) Conservation refugees: the hundred-year conflict between global conservation and native peoples. MIT Press, Cambridge, Massachusetts.

Eichenberg D, Bowler DE, Bonn A, Bruelheide H, Grescho V, Harter D, Jandt U, May R, Winter M, Jansen F (2021) Widespread decline in central European plant diversity across six decades. Global Change Biology 27:1097–1110. https://doi.org/10.1111/gcb.15447

Ellenberg H, Weber H, Düll R, Wirth V, Werner W, Paulißen D (1991) Zeigerwerte von Pflanzen in Mitteleuropa. Scr Geobot 18,1–248. Goltze, Göttingen, Germany.

Eufemia L, Wawrzynowicz I, Bonatti M, Partelow S, Fischer J, Sieber S (2023) Governing landscapes: an agenda for the assessment of grasslands and savannahs. Frontiers in Sustainable Resource Management 2, 1134393. https://doi.org/10.3389/fsrma.2023.1134393

Feurdean A, Ruprecht E, Molnár Z, Hutchinson SM, Hickler T (2018) Biodiversity-rich European grasslands: ancient, forgotten ecosystems. Biological Conservation 228:224–232. https://doi.org/10.1016/j.biocon.2018.09.022

Fuhlendorf SD, Engle DM, Kerby JAY, Hamilton R (2009) Pyric herbivory: rewilding landscapes through the recoupling of fire and grazing. Conservation Biology 23:588–598. https://doi.org/10.1111/j.1523-1739.2008.01139.x

IPBES (2019) Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. IPBES, Bonn, Germany

Jandt U, Bruelheide H, Jansen F, Bonn A, Grescho V, Klenke RA, Sabatini FM, Bernhardt-Römermann M, Blüml V, Dengler J (2022) More losses than gains during one century of plant biodiversity change in Germany. Nature 611:512–518. https://doi.org/10.1038/s41586-022-05320-w

Landolt E (1895) Der Wald, seine Verjüngung, Pflege und Benutzung: bearbeitet für das Schweizervolk. Schulthess, Zurich, Switzerland. https://doi.org/10.5962/bhl.title.29941

Lewis SL, Maslin MA (2015) Defining the anthropocene. Nature 519:171–180. https://doi.org/10.1038/nature14258

Lewis SL, Wheeler CE, Mitchard ETA, Koch A (2019) Restoring natural forests is the best way to remove atmospheric carbon. Nature 568:25–28. https://doi.org/10.1038/d41586-019-01026-8

Mace GM, Barrett M, Burgess ND, Cornell SE, Freeman R, Grooten M, Purvis A (2018) Aiming higher to bend the curve of biodiversity loss. Nature Sustainability 1:448–451. https://doi.org/10.1038/s41893-018-0130-0

McDowell NG, Allen CD (2015) Darcy's law predicts widespread forest mortality under climate warming. Nature Climate Change 5:669–672. https://doi.org/10.1038/nclimate2641

Metzing D, Hofbauer N, Ludwig G, Matzke-Hajek G (2018) Rote Liste gefährdeter Tiere, Pflanzen und Pilze Deutschlands: Pflanzen/Redaktion: Detlev Metzing, Natalie Hofbauer, Gerhard Ludwig und Günter Matzke-Hajek. Bundesamt für Naturschutz

Overbeck GE, Müller SC, Fidelis A, Pfadenhauer J, Pillar VD, Blanco CC, Boldrini II, Both R, Forneck ED (2007) Brazil's neglected biome: the south Brazilian Campos. Perspectives in Plant Ecology, Evolution and Systematics 9:101–116. https://doi.org/10.1016/j.ppees.2007.07.005

Overbeck GE, Vélez-Martin E, da Silva ML, Anand M, Baeza S, Carlucci MB, Dechoum MS, Durigan G, Fidelis A, Guido A (2022) Placing Brazil's grasslands and savannas on the map of science and conservation. Perspectives in Plant Ecology, Evolution and Systematics 56:125687. https://doi.org/10.1016/j.ppees.2022.125687

Overbeck GE, Vélez-Martin E, Scarano FR, Lewinsohn TM, Fonseca CR, Meyer ST, Müller SC, Ceotto P, Dadalt L, Durigan G (2015) Conservation in Brazil needs to include non-forest ecosystems. Diversity and Distributions 21:1455–1460. https://doi.org/10.1111/ddi.12380

Pastore MA, Hobbie SE, Reich PB (2021) Sensitivity of grassland carbon pools to plant diversity, elevated CO_2, and soil nitrogen addition over 19 years. Proceedings of the National Academy of Sciences 118:e2016965118. https://doi.org/10.1073/pnas.2016965118

Pausas JG, Bond WJ (2019) Humboldt and the reinvention of nature. Journal of Ecology 107:1031–1037. https://doi.org/10.1111/1365-2745.13109

Rohatyn S, Yakir D, Rotenberg E, Carmel Y (2022) Limited climate change mitigation potential through forestation of the vast dryland regions. Science 377:1436–1439. https://doi.org/10.1126/science.abm9684

RS (2014) Decreto Estadual no 52.109, de 01 Dezembro de 2014. Declara as espécies da flora nativa ameaçadas de extinção no Estado do Rio Grande do Sul di Sacco A, Hardwick KA, Blakesley D, Brancalion PHS, Breman E, Cecilio Rebola L, Chomba S, Dixon K, Elliott S, Ruyonga G (2021) Ten golden rules for reforestation to optimize carbon sequestration, biodiversity recovery and livelihood benefits. Global Change Biology 27:1328–1348. https://doi.org/10.1111/gcb.15498

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. https://doi.org/10.1038/s41558-019-0405-0

Silveira FAO, Arruda AJ, Bond W, Durigan G, Fidelis A, Kirkman K, Oliveira RS, Overbeck GE, Sansevero JBB, Siebert F (2020) Myth-busting tropical grassy biome restoration. Restoration Ecology 28:1067–1073. https://doi.org/10.1111/rec.13202

Staude IR, Pereira HM, Daskalova GN, Bernhardt-Römermann M, Diekmann M, Pauli H, Van Calster H, Vellend M, Bjorkman AD, Brunet J (2022) Directional turnover towards larger-ranged plants over time and across habitats. Ecology Letters 25:466–482. https://doi.org/10.1111/ele.13937

Steinbeiss S, Beßler H, Engels C, Temperton VM, Buchmann N, Roscher C, Kreutziger Y, Baade J, Habekost M, Gleixner G (2008) Plant diversity positively affects short-term soil carbon storage in experimental grasslands. Global Change Biology 14:2937–2949. https://doi.org/10.1111/j.1365-2486.2008.01697.x

Svenning J-C (2002) A review of natural vegetation openness in north-western Europe. Biological Conservation 104:133–148. https://doi.org/10.1016/S0006-3207(01)00162-8

Tansley AG (1911) Types of British vegetation. Cambridge, England: Cambridge University Press. https://doi.org/10.5962/bhl.title.55266

Temperton VM, Buchmann N, Buisson E, Durigan G, Kazmierczak Ł, Perring MP, de Sá DM, Veldman JW, Overbeck GE (2019) Step back from the forest and step up to the Bonn Challenge: how a broad ecological perspective can promote successful landscape restoration. Restoration Ecology 27:705–719. https://doi.org/10.1111/rec.12989

Tilman D, Downing JA (1994) Biodiversity and stability in grasslands. Nature 367:363–365. https://doi.org/10.1038/367363a0

Veldman JW, Buisson E, Durigan G, Fernandes GW, le Stradic S, Mahy G, Negreiros D, Overbeck GE, Veldman RG, Zaloumis NP (2015) Toward an old-growth concept for grasslands, savannas, and woodlands. Frontiers in Ecology and the Environment 13:154–162. https://doi.org/10.1890/140270

Vera FWM (2000) Grazing ecology and forest history. Wallingford, UK: CABI Publishing. https://doi.org/10.1079/9780851994420.0000

Vicente-Serrano SM, Gouveia C, Camarero JJ, Beguería S, Trigo R, López-Moreno JI, Azorín-Molina C, Pasho E, Lorenzo-Lacruz J, Revuelto J (2013) Response of vegetation to drought time-scales across global land biomes. Proceedings of the National Academy of Sciences 110:52–57. https://doi.org/10.1073/pnas.1207068110

Wang L, Pedersen PBM, Svenning J-C (2023) Rewilding abandoned farmland has greater sustainability benefits than afforestation. npj Biodiversity 2:5. https://doi.org/10.1038/s44185-022-00009-9

White RP, Murray S, Rohweder M, Prince SD, Thompson KM (2000) Grassland ecosystems. World Resources Institute, Washington D.C.

Yang Y, Tilman D, Furey G, Lehman C (2019) Soil carbon sequestration accelerated by restoration of grassland biodiversity. Nature Communications 10:1–7. https://doi.org/10.1038/s41467-019-08636-w

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