ACADEMIA BIOLOGY

Mini Review
Published: 2025-01-24
https://doi.org/10.20935/AcadBiol7502

Accelerating contributions of restoration ecology for enhancing natural climate solutions

Timothy R. Seastedt[1,*]

Academic Editors: Benoit Vanhee, Kevin Cianfaglione, Andre J. van Wijnen

Abstract

Ecological restoration efforts protect and benefit the biota we value, contribute to clean air and water, and enhance human health and mental well-being. Such efforts, however, are futile unless we concurrently address the climate crisis. Many restoration actions implicitly or explicitly provide climate mitigation outcomes, and these need to be emphasized and prioritized. Local actions that collectively have global impacts need greater participation of academics, managers, policymakers, and stakeholders. Such actions will reduce the current knowing-versus-doing gap, speed up essential activities, and increase the spatial extent of restoration efforts that benefit climate solutions and provide community resilience to extreme climate events. All landscapes, regardless of the extent of human impacts, are potentially eligible for these actions. Priorities of management that are neutral or negative with respect to climate mitigation need to be reevaluated given the need and availability of similar actions that facilitate climate mitigation. If traditional management programs such as urban construction, tillage, landscaping, roads, trails, and weed control are subsumed within an enhanced climate solutions framework, restoration emerges as the common management theme. Of particular importance, programs that both repair and prepare for current and anticipated catastrophic climatic events deserve priority status. A relatively new paradigm created by land managers, the "Restore-Accept-Direct" model, provides a framework where conservation, human well-being, and enhanced climate solution outcomes can be simultaneously achieved.

Keywords: *carbon drawdown, ecosystem services, natural climate solutions*

Citation: Seastedt TR. Accelerating contributions of restoration ecology for enhancing natural climate solutions. *Academia Biology* 2025;3. https://doi.org/10.20935/AcadBiol7502

1. Introduction

Restoration ecology exploded as an applied science toward the end of the last century and currently has the potential to function as a mechanism of socioecological transformative change [1]. Restoration ecology was argued "to be one of the most important fields in the coming century" [2]. In recent years, a broader interpretation of restoration has included human-dominated landscapes that have been continuously altered for millennia [3]. Restoration efforts also teach humility, i.e., we do not know as much as we thought we did. However, the importance and significance of this discipline both then and now remains clear. Urgency is called for; the ongoing global landscape degradation and the increasing frequency and intensity of extreme climate events justified the United Nations (UN) resolution declaring the 2021–2030 interval the "Decade on Ecosystem Restoration" [4].

Aldo Leopold, an eminent ecologist and perhaps the greatest environmental ethicist of the last century, clearly understood and articulated the principles of ecological restoration [5]. He recognized that any community contained "parts," i.e., species or objects, and these parts had functions that produced outcomes in terms of such community or ecosystem characteristics as water quality or plant productivity. If we protect the parts and understand how biotic communities are constructed and function, then we should be able to reassemble them after these have been degraded by human or natural causes. Restoration efforts usually demonstrated that complete or exact reconstructions were rare, and this likelihood has diminished with time. This is due to topographic, hydrological, and physical or chemical changes to landscapes and soils. These changes either drive or accompany the loss of species and the presence of relatively new organisms, including a suite of largely unknown soil microbes and soil animals introduced into landscapes either deliberately or accidently by humans. Furthermore, these new configurations of organisms are interacting with or without potentially novel climate conditions [6], although novel climates are becoming the norm. In recognition of this, restoration ecologists have suggested other terminology that recognizes the program's limitations, such as "ecosystem rehabilitation" [7] or "intervention ecology" [8]. For scaling restoration ecology up to the planetary level, the term "biosphere stewardship" is appropriate [9]. The activity continues to benefit from a wealth of new findings and conceptual frameworks [10], including paleoecological findings that provide insights into rates of change, responses, and potential recovery of communities to changing climates and catastrophic events [11–13]. Given that the

[1]Department of Ecology and Evolutionary Biology and Institute of Arctic and Alpine Research, University of Colorado, Boulder, CO 80309, USA.
*email: timothy.seastedt@colorado.edu

UN chose to use the term "restoration," it remains the most common identifier of the science efforts that attempt to change degraded systems into something of greater value.

We are now about halfway through the UN decade of ecosystem restoration, and efforts, while numerous and significant, remain underfunded and underemphasized as serious contributions to climate mitigation. While academics will continue to argue details, there is no doubt that the global practice of restoration ecology can contribute to the slowing and stabilization of the planet's temperature [14–16] and can be implemented now.

Much of restoration ecology involves manipulating communities. Simply put, plants affect climate [17], and thus impact local heating, greenhouse gases, and water dynamics. This fact becomes the dominant tool for natural climate solutions (NCS). Physical objects and materials can sometimes substitute for these plant effects, and in the built environments of urban areas, these can be significant tools for achieving NCS goals [18].

Priority restoration actions focus on activities that will specifically "increase carbon drawdown" [19], and the major nexus of restoration and climate mitigation involves removing carbon in the form of greenhouse gases from the atmosphere. Restoration that is directed at biological conservation can concurrently maximize the ability of biotic communities to contribute to NCS, but alterations of human-dominated environments such as agricultural and urban areas can also be used for this. The goal of this review is to demonstrate that all the pieces are in place to conduct these actions. Existing data and analyses indicate that compelling outcomes can be generated by restoration ecology as the mechanism for NCS. Furthermore, at the time of writing this review, the huge impacts of the increasing frequency and intensity of extreme climate events, including catastrophic wildfires, floods, and both terrestrial-based (e.g., wind storms, tornados) and coastal storms (hurricanes), are generating a compelling need for global restoration efforts. With crisis comes opportunity, and priority restoration activities following these catastrophes can include those measures that provide enhanced NCS. Clearly, if the focus is on greenhouse gas removal, large-area restorations become a priority.

2. What are the key ecological factors that provide the maximum natural climate solution benefits?

This review assumes substantial ecological knowledge on the part of its readers. As one who has engaged in the education of stakeholders in NCS activities, the author has discovered that while organisms are very much understandable objects with functions that almost everyone can appreciate, understanding the consequences of these biotic actions in terms of the physical and chemical changes caused by the collective interactions of organisms often results in a fuzzy abstraction. It is easier to engage stakeholders in conservation actions related to the health of various organisms than to engage stakeholders in the fine-tuning of the biogeochemistry of ecosystems. The latter can involve some complicated measurements requiring substantial instrumentation, and few are trained to do this. Relating plant growth to carbon sequestration to atmospheric temperatures can be taxing [20]. If the compelling focus of enhanced NCS is to increase carbon drawdown and this process appears opaque and not quantitative to readers, then a visit to the carbon drawdown website or similar sites not funded by vested interests can be helpful [21, 22]. What's important is to understand that within any regional area, the type of biotic community you wish to create or restore can definitely affect the short- and long-term NCS outcomes. Here, those restorations that provide the greatest diversity of benefits while maximizing NCS potentials for a specific area are emphasized.

"Nature's benefits" or "ecosystem services" are those direct and indirect outcomes and products provided by communities that we value. Full disclosure requires the acknowledgment that nature provides disservices as well, and restorations, while net-positive actions, can produce disservices. Ecosystem services also include cultural and individual contexts such as aesthetics and beauty. While recognizing that this classification can be observer dependent, if a service can be tallied as "a win," then how many "wins" can a restoration project provide? An incomplete list is provided in **Table 1**, where 11 relatively common outcomes of restoration are listed. Again, it is worth noting that the restoration project may be conducted for reasons independent of NCS, but the NCS co-benefit can be large.

Table 1 • The ecosystem services provided by a restoration project associated with enhanced natural climate solutions.

Service	Reference(s)
Preservation of threatened species	[23]
Increased species diversity	[24, 25]
Enhanced plant productivity	[26, 27]
Enhanced carbon storage (carbon drawdown)	[28]
Local cooling effects	[29]
Reduced runoff, reduced flood threat	[30]
Reduced wildfire threat	[31, 32]
Reduction in undesirable species	[33]
Increased physical health of participants	[34]
Increased mental well-being of adults and adolescents	[35, 36]
Education and empowerment	[37]

If the key-enhanced NCS goal is to remove a greenhouse gas from the atmosphere, then the capabilities of the various biotic communities to store the necessary carbon in the greenhouse gas provide insights into the relative value of prioritizing restoration efforts. Storage into living plant materials and dead organic materials in the soil have been measured and generalized for mid-latitude biotic communities (**Figure 1**) [38]. Of significance in many landscapes, carbon stored in the soil is much less vulnerable to catastrophic wildfires. While **Figure 1** is a generalization unlikely to accurately describe any specific locality, the graph can provide useful insights and potential priorities for NCS actions. Wetlands are by far the best at soil carbon storage, whereas our conventional agricultural systems are the worst. A surprise to many, grasslands can be better at storing carbon in the soil than forests. Any effort to convert conventionally tilled cropland to reduced tillage or no-till agriculture may generate a large benefit, and the area involved in these conversions is very large. Per unit area, restorations of wetlands are likely the best way to remove carbon from the atmosphere over the long term. Carbon can be moved into living plant materials much faster than it can be stored in soils. Plants are the soil carbon pumps, and revegetation of appropriate habitats with anticipated long-term carbon storage outcomes is a reality. Can these activities be scaled up to produce meaningful results on a global scale? The answer, while often qualified, is yes [39–41].

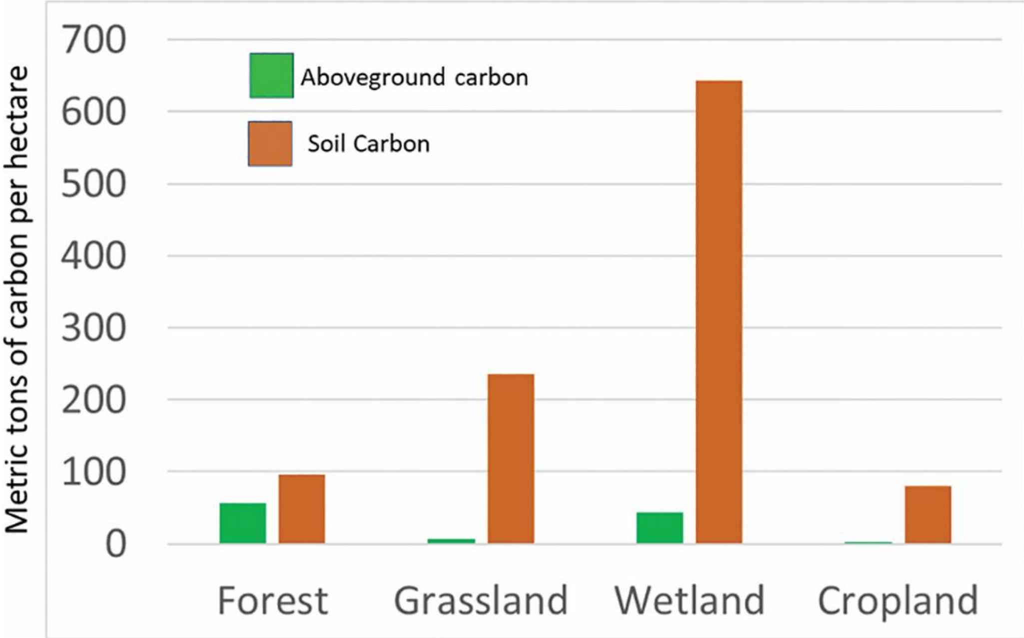

Figure 1 • Estimates of carbon storage capability by various terrestrial ecosystems in the temperate zones of the planet. The carbon in the aboveground plant biomass (green bars) is uniformly lower than that found in soils (brown bars) and the above/below ratios clearly differ among communities (data from Neufeld and Smith [38]).

3. Operating manuals for natural climate solutions

The general principles for developing and operating restoration efforts with large NCS emphasis have been articulated, with a large number of articles focused on specific ecosystem types, including natural, agricultural, and built environments [42–44]. Of obvious importance, such efforts need to be "fine-tuned" for specific climates and social goals and, therefore, have a local focus [45], as well as deal with how new climatic events and conditions will influence restoration efforts [46, 47]. Furthermore, programs need to understand both the economic and political conditions that are necessary to facilitate successful restoration efforts [48, 49]. To achieve the identified management goals, a "co-production science" approach [50, 51] can speed up the planning and doing process. This approach specifically demands that stakeholders, academics, managers, and other professionals be involved from the planning stage onward. While restoration ecology efforts often have experimental dimensions and must include monitoring to be science-based, the projects themselves can be led by citizen scientists, nonprofit organizations, and land managers (cf. [52, 53]).

Using co-production procedures, managers and applied ecologists have advocated the "Resist-Accept-Direct" (RAD) frameworks for natural climate solution actions [54–56]. As the names imply, managers, in conjunction with stakeholders and academics, determine if management actions should attempt to restore a damaged site, potentially accept the changes that have occurred, or opt to proactively restructure a biotic system to achieve management goals. All options demand local expertise and the recognition that site-specific outcomes are possible. The management focuses on what we want and need rather than on things we do not want, and concurrently identify explicit goals and pitfalls. This management approach also is compatible with factoring acceptable components of climate change adaptation strategies [57]. Requiring all restoration actions to be valued in terms of their contributions to enhanced NCS should be a prominent part of these actions.

4. Case studies: rewetting in both upland and lowland habitats has large enhanced natural climate solution values

An endemic bird found in Colorado, USA, the Gunnison sage grouse, has been listed as a threatened species due to the birds' low population numbers, low population growth trends, and relatively low local distribution. Beginning in 2012, scientists, managers, and stakeholders began what has become a long-term and ongoing restoration effort to enhance the survivorship of this species [26]. The key activity was to restore meadows that had been eroded by decades of cattle use and roads. Downcutting of these meadow soils had resulted in the vegetation drying out, with grasslands slowly converted into shrublands. These shrublands did not provide sufficient-quality food resources for young grouse, thereby enhancing the mortality of the birds. A variety of "low-tech" erosion control and water retention structures were employed to rewet these meadows (**Figure 2**) [58]. The outcome, while still being assessed, suggests that the number of birds has increased while contributing to virtually all of the ecological services listed in **Table 1**. Thus, while the focus of the restoration was to save a rare species, the climate mitigation benefits, specifically enhanced carbon drawdown, were evident from this effort. The techniques of rewetting across multiple landscape types have been detailed [59, 60], and similar projects are now underway at a much larger spatial scale to benefit similar species.

Figure 2 • Low-tech "geoengineering." A group of restoration volunteers examine their work three years after the installation of structures designed for erosion control, rewetting of grassland meadows, and reestablishing the flood plain on sites that were previously being drained and converted to sagebrush. Photo by Cathy Tate.

The North American and Eurasian beavers were hunted to near extinction and extirpated from a huge portion of the northern hemisphere. With the loss of this animal, a concurrent dry-down of many landscapes occurred, and in most cases, the landscape was transformed solely by the animal's loss [61]. Later, agriculture that exploited the fertility of former beaver meadows tended to further dry down these lowland areas as well as enhance carbon losses to the atmosphere. The large impacts of these "ecosystem engineers" have been rediscovered, and the suite of restoration benefits have been identified [62] including a reduction in impacts of wildfires [25]. Low-tech structures that slow runoff, rewet soils, and can mimic beaver dams can transform landscapes [63]. While uncertainties remain, the enhanced NCS and related ecosystem service values by restoring the resilience of river corridors are huge [64]. Overall, restoring wetlands appears to be one of the most important, if not the most important, restoration activity in North America [65].

While planting or replanting trees may be an equally or more important activity on a large portion of the planet, the threat of losing the carbon found in aboveground plant biomass by wildfire means that reforestation is not appropriate in many communities [66]. This is true particularly in seasonally dry, semiarid, and arid environments that make up a large percentage of the terrestrial ecosystems [67]. However, planting savannas (widely dispersed trees in grasslands) in arid and semiarid regions that once were forests may be appropriate as these systems, and these can provide multiple ecological services and NCS. In humid environments, tree planting most often can provide substantial and the most important carbon drawdown and cooling benefits [68].

Planting and seeding dominates much of restoration ecology, but the restructuring of landscapes to correct damage from historical land use or redirecting runoff from our many impermeable surfaces of urban, and suburban areas also can provide enhanced NCS values [69]. The goal of this action is to spread this runoff over permeable surfaces, rewetting the soil sponge, enhancing plant-driven carbon drawdown, and recharging the local aquifers that collectively reduce water loss. Trails and roads should be looked at from the perspective of providing water subsidies to their surrounding landscapes. The economics of doing this are compelling in many areas as water becomes an even more limited resource in many regions of the world.

5. What's holding us up?

We cannot simply substitute enhanced carbon drawdown for our increased carbon emissions to solve the climate crisis. That said, restoration actions generating enhanced carbon drawdown can often over-perform in terms of their climate benefits but are underfunded [15]. Climate change itself is often not helping here in that costly extreme weather events are increasing in intensities and frequencies, and in order for restoration to score enhanced NCS values, we must do more than neutralize the increased losses due to extreme climate events. Currently, most of the public funding is directed at reactive measures to repair systems from wildfires, floods, windstorms, and hurricanes. However, as discussed earlier, these reactions to the current manifestations to the climate crisis can be enhanced with proactive measures that will contribute to NCS. Why restore a site if only to fall victim to another catastrophic event? Rather, restore and reconfigure these systems to have maximum resilience to such events and the largest NCS benefits for these landscapes. For example, restoring recently incinerated closed-canopy forests to savannas which can largely survive the next wildfire can also provide needed biodiversity and NCS benefits. Those species requiring old-growth or closed-canopy forests will require special attention, but all of these goals are possible if regional planning provides the appropriate RAD management actions required to ameliorate climate risk and benefit conservation goals.

Restoration is a model for co-production science actions. Participation in restoration efforts, including urban actions, can benefit all stakeholders, including youth, but socioeconomic factors constrain this opportunity and need to be addressed to provide a form of environmental justice for urban areas [70]. Programs designed to increase income equity and address environmental justice therefore can contribute both directly and indirectly to NCS. A climate conservation corps, modified from the incredibly impactful civilian conservation corps of the last century [71], has the potential to score all of the "wins" identified in **Table 1**. Community health and environmental interests now provide economic benefits that justify these actions, and once these are recognized by policymakers, then much larger projects such as those envisioned by individuals such as Ties Van Der Hoeven and John D. Lui (as described in Schwartz's study [72]) can become mainstream. Academics can perform these actions as part of their service contributions, land managers receive credit for doing their jobs, and stakeholders can join in these activities as volunteers for multiple self-interest reasons. Collectively, more concerted ecological restoration efforts represent modest but immediate, cost-effective, and important contributions to climate crisis solutions.

Acknowledgments

This review was informed by multiple decades of restoration work conducted by students and volunteers who were often supported by the University of Colorado and a nonprofit, Wildlands Restoration Volunteers. This effort benefited from comments, corrections, and suggestions on earlier versions of the review provided by Kevin Cianfaglione and Benoit Vanhee, and several anonymous reviewers.

Funding

The author declares no financial support for the research, authorship, or publication of this article.

Author contributions

The author confirms sole responsibility for this work. The author approves of this work and takes responsibility for its integrity.

Conflict of interest

The author declares no conflict of interest.

Data availability statement

Data supporting these findings are available within the article, at https://doi.org/10.20935/AcadBiol7502, or upon request.

Institutional review board statement

Not applicable.

Informed consent statement

Not applicable.

Additional information

Received: 2024-11-02

Accepted: 2025-01-09

Published: 2025-01-24

Academia Biology papers should be cited as *Academia Biology 2025*, ISSN 2837-4010, https://doi.org/10.20935/AcadBiol7502. The journal's official abbreviation is *Acad. Biol.*

Publisher's note

Copyright

References

1. Tedesco AM, López-Cubillos S, Chazdon R, Rhodes JR, Archibald CL, Pérez-Hämmerle KV, et al. Beyond ecology: ecosystem restoration as a process for social-ecological transformation. Trends Ecol Evol. 2023;38(7):643–53. doi: 10.1016/j.tree.2023.02.007
2. Hobbs RJ, Harris JA. Restoration ecology: repairing the earth's ecosystems in the new millennium. Restoration Ecol. 2001;9(2):239–46. doi: 10.1046/j.1526-100x.2001.009002239.x
3. Hobbs RJ, Higgs E, Hall CM, Bridgewater P, Chapin III FS, Ellis EC, et al. Managing the whole landscape: historical, hybrid, and novel ecosystems. Front Ecol Environ. 2014; 12(10):557–64. doi: 10.1890/130300
4. Fischer J, Riechers M, Loos J, Martin-Lopez B, Temperton VM. Making the UN decade on ecosystem restoration a social-ecological endeavour. Trends Ecol Evol. 2021;36(1): 20–8. doi: 10.1016/j.tree.2020.08.018
5. Leopold A. A sand county almanac: with essays on conservation from Round River. New York: Ballantine Books NY; 1986 (originally published 1949).

6. Seastedt TR, Hobbs RJ, Suding KN. Management of novel ecosystems: are novel approaches required? Front Ecol Environ. 2008;6(10):547–53. doi: 10.1890/070046
7. Choi YD. Restoration ecology to the future: a call for new paradigm. Restor Ecol. 2007;15(2):351–3. doi: 10.1111/j.1526-100X.2007.00224.x
8. Hobbs RJ, Hallett LM, Ehrlich PR, Mooney HA. Intervention ecology: applying ecological science in the twenty-first century. BioScience. 2011;61(6):442–50. doi: 10.1525/bio.2011.61.6.6
9. Rockström J, Beringer T, Hole D, Griscom B, Mascia MB, Folke C, et al. We need biosphere stewardship that protects carbon sinks and builds resilience. Proc Natl Acad Sci. 2021;118(38): e2115218118. doi: 10.1073/pnas.2115218118
10. Suding KN. Toward an era of restoration in ecology: successes, failures, and opportunities ahead. Ann Rev Ecol Evol Syst. 2011; 42(1):465–87. doi: 10.1146/annurev-ecolsys-102710-145115
11. Finsinger W, Bigler C, Schwörer C, Tinner W. Rates of palaeo-ecological change can inform ecosystem restoration. Biogeosciences. 2024;21(7):1629–38. doi: 10.5194/bg-21-1629-2024
12. Fordham DA, Jackson ST, Brown SC, Huntley B, Brook BW, Dahl-Jensen D, et al. Using paleo-archives to safeguard biodiversity under climate change. Science. 2020;369(6507): eabc5654. doi: 10.1126/science.abc5654
13. Manzano S, Julier AC, Dirk CJ, Razafimanantsoa AH, Samuels I, Petersen H, et al. Using the past to manage the future: the role of palaeoecological and long-term data in ecological restoration. Restor Ecol. 2020;28(6):1335–42. doi: 10.1111/rec.13285
14. Fargione JE, Bassett S, Boucher T, Bridgham SD, Conant RT, Cook-Patton SC, et al. Natural climate solutions for the United States. Sci Adv. 2018;4(11):eaat1869. doi: 10.1126/sciadv.aat1869
15. Girardin CA, Jenkins S, Seddon N, Allen M, Lewis SL, Wheeler CE, et al. Nature-based solutions can help cool the planet—if we act now. Nature. 2021;593:191–94. doi: 10.1038/d41586-021-01241-2
16. Ellis PW, Page AM, Wood S, Fargione J, Masuda YJ, Carrasco V, et al. The principles of natural climate solutions. Nat Commun. 2024;15:547. doi: 10.1038/s41467-023-44425-2
17. Parmesan C, Hanley ME. Plants and climate change: complexities and surprises. Ann Bot. 2015;116(6):849–64. doi: 10.1093/aob/mcv169
18. Bulkeley H. Cities and climate change. Milton Park, Abingdon, Oxfordshire: Routledge; 2013.
19. Silva LC, Wood MC, Johnson BR, Coughlan MR, Brinton H, McGuire K, et al. A generalizable framework for enhanced natural climate solutions. Plant Soil. 2022;479(1):3–24. doi: 10.1007/s11104-022-05472-8
20. Johnson EJ, Sugerman ER, Morwitz VG, Johar GV, Morris MW. Widespread misestimates of greenhouse gas emissions suggest low carbon competence. Nat Climate Change. 2024; 21:1–8. doi: 10.1038/s41558-024-02032-z
21. Anonymous Project Drawdown. Land sinks. 2024 [cited 2024 Sep 7]. Available from: https://drawdown.org/sectors/land-sinks
22. Hawken P, ed. Drawdown: The most comprehensive plan ever proposed to reverse global warming. Westminster, London: Penguin; 2017.
23. Casazza ML, Overton CT, Bui TV, Hull JM, Albertson JD, Bloom VK, et al. Endangered species management and ecosystem restoration: finding the common ground. Ecol Soc. 2016;21(1):19. doi: 10.5751/ES-08134-210119
24. Atkinson J, Brudvig LA, Mallen-Cooper M, Nakagawa S, Moles AT, Bonser SP. Terrestrial ecosystem restoration increases biodiversity and reduces its variability, but not to reference levels: a global meta-analysis. Ecol Lett. 2022; 25(7):1725–37. doi: 10.1111/ele.14025
25. Standish RJ, Parkhurst T. Interventions for resilient nature-based solutions: an ecological perspective. J Ecol. 2024;112: 2502–9. doi: 10.1111/1365-2745.14377
26. Silverman NL, Allred BW, Donnelly JP, Chapman TB, Maestas JD, Wheaton JM, et al. Low-tech riparian and wet meadow restoration increases vegetation productivity and resilience across semiarid rangelands. Restor Ecol. 2019; 27(2):269–78. doi: 10.1111/rec.12869
27. Furey GN, Tilman D. Plant biodiversity and the regeneration of soil fertility. Proc Natl Acad Sci. 2021;118(49):e21113 21118. doi: 10.1073/pnas.2111321118
28. Bossio DA, Cook-Patton SC, Ellis PW, Fargione J, Sanderman J, Smith P, et al. The role of soil carbon in natural climate solutions. Nat Sustain. 2020;3(5):391–8. doi: 10.1038/s41893-020-0491-z
29. Zimmermann B, Kruber S, Nendel C, Munack H, Hildmann C. Assessing the cooling potential of climate change adaptation measures in rural areas. J Environ Manag. 2024; 366:121595. doi: 10.1016/j.jenvman.2024.121595
30. Acreman M, Holden J. How wetlands affect floods. Wetlands. 2013;33:773–86. doi: 10.1007/s13157-013-0473-2
31. Fairfax E, Whittle A. Smokey the beaver: beaver-dammed riparian corridors stay green during wildfire throughout the western United States. Ecol Appl. 2020;30:e02225. doi: 10.1002/eap.2225
32. Huffman DW, Roccaforte JP, Springer JD, Crouse JE. Restoration applications of resource objective wildfires in western US forests: a status of knowledge review. Fire Ecol. 2020;16:1–3. doi: 10.1186/s42408-020-00077-x
33. Weidlich EW, Flórido FG, Sorrini TB, Brancalion PH. Controlling invasive plant species in ecological restoration: a global review. J Appl Ecol. 2020;57(9):1806–17. doi: 10.1111/1365-2664.13656
34. Marselle MR, Hartig T, Cox DT, De Bell S, Knapp S, Lindley S, et al. Pathways linking biodiversity to human health: a conceptual framework. Environ Int. 2021;150:106420. doi: 10.1016/j.envint.2021.106420
35. Nabhan GP, Orlando L, Smith Monti L, Aronson J. Hands-on ecological restoration as a nature-based health intervention: reciprocal restoration for people and ecosystems. Ecopsychol. 2020;12(3):195–202. doi: 10.1089/eco.2020.0003

36. Nguyen L, Walters J. Benefits of nature exposure on cognitive functioning in children and adolescents: a systematic review and meta-analysis. J Environ Psychol. 2024;96: 102336. doi: 10.1016/j.jenvp.2024.102336
37. Ardoin NM, Bowers AW, Gaillard E. Environmental education outcomes for conservation: a systematic review. Biol Conserv. 2020;241:108224. doi: 10.1016/j.biocon.2019. 108224
38. Neufeld D, Smith M. Visualizing carbon storage in earth's ecosystems. Visual Capitalist. 2022 [cited 2024 Jan 11]. Available from: https://www.visualcapitalist.com/sp/visualizing-carbon-storage-in-earths-ecosystems/
39. Buma B, Gordon DR, Kleisner KM, Bartuska A, Bidlack A, DeFries R, et al. Expert review of the science underlying nature-based climate solutions. Nat Clim Change. 2024; 14(4):402–6. doi: 10.1038/s41558-024-01960-0
40. Novick KA, Metzger S, Anderegg WR, Barnes M, Cala DS, Guan K, et al. Informing nature-based climate solutions for the United States with the best-available science. Glob Change Biol. 2022;28(12):3778–94. doi: 10.1111/gcb.16156
41. Seddon N. Harnessing the potential of nature-based solutions for mitigating and adapting to climate change. Science. 2022; 376(6600):1410–6. doi: 10.1126/science.abn9668
42. Chapin FS, Carpenter SR, Kofinas GP, Folke C, Abel N, Clark WC, et al. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. Trends Ecol Evol. 2010; 25(4):241–9. doi: 10.1016/j.tree.2009.10.008
43. Cook-Patton SC, Drever CR, Griscom BW, Hamrick K, Hardman H, Kroeger T, et al. Protect, manage and then restore lands for climate mitigation. Nature Clim Change. 2021;11(12):1027–34. doi: 10.1038/s41558-021-01198-0
44. Seddon N, Smith A, Smith P, Key I, Chausson A, Girardin C, et al. Getting the message right on nature-based solutions to climate change. Glob Change Biol. 2021;27(8):1518–46. doi: 10.1111/gcb.15513
45. Brown MA, Dwivedi P, Mani S, Matisoff D, Mohan JE, Mullen J, et al. A framework for localizing global climate solutions and their carbon reduction potential. Proc Natl Acad Sci. 2021;118(31):e2100008118. doi: 10.1073/pnas. 2100008118
46. Rader AJ, Chiquoine LP, Weigand JF, Perkins JL, Munson SM, Abella SR. Biotic and abiotic treatments as a bet-hedging approach to restoring plant communities and soil functions. Restor Ecol. 2022;30(2):e13527. doi: 10.1111/ rec.13527
47. Svejcar LN, Davies KW, Ritchie AL. Ecological restoration in the age of apocalypse. Glob Change Biol. 2023;29(17):4706–10. doi: 10.1111/gcb.16809
48. Osborne T, Brock S, Chazdon R, Chomba S, Garen E, Gutierrez V, et al. The political ecology playbook for ecosystem restoration: principles for effective, equitable, and transformative landscapes. Glob Environ Change. 2021;70:102320. doi: 10.10 16/j.gloenvcha.2021.102320
49. Bradbury RB, Butchart SH, Fisher B, Hughes FM, Ingwall-King L, MacDonald MA, et al. The economic consequences of conserving or restoring sites for nature. Nat Sustain. 2021;4(7):602–8. doi: 10.1038/s41893-021-00692-9
50. Bremer S, Meisch S. Co-production in climate change research: reviewing different perspectives. WIREs Clim Change. 2017; 8(6):e482. doi: 10.1002/wcc.482
51. Bamzai-Dodson A, Cravens AE, Wade AA, McPherson RA. Engaging with stakeholders to produce actionable science: a framework and guidance. Weather Clim Soc. 2021;13(4): 1027–41. doi: 10.1175/WCAS-D-21-0046.1
52. Cross MS, Oakes LE, Kretser HE, Bredehoft R, Dey P, Mahoney A, et al. Tackling the science usability gap in a warming world: co-producing useable climate information for natural resource management. Environ Manag. 2022; 70(6):881–95. doi: 10.1007/s00267-022-01718-4
53. Selby LB, Carter SK, Haby TS, Wood DJA, Bamzai-Dodson A, Anderson PJ, et al. A toolkit for coproducing actionable science to support public land management. 2024 [cited 2024 Aug 29]. Available from: https://www.ntc.blm.gov/ krc/legacy/course/1189
54. Lynch AJ, Thompson LM, Beever EA, Cole DN, Engman AC, Hawkins Hoffman C, et al. Managing for RADical ecosystem change: applying the Resist-Accept-Direct (RAD) framework. Front Ecol Environ. 2021;19(8):461–9. doi: 10.1002/fee.2377
55. Crausbay SD, Sofaer HR, Cravens AE, Chaffin BC, Clifford KR, Gross JE, et al. A science agenda to inform natural resource management decisions in an era of ecological transformation. BioScience. 2022;72(1):71–90. doi: 10.1093/biosci/biab102
56. Schuurman GW, Cole DN, Cravens AE, Covington S, Crausbay SD, Hoffman CH, et al. Navigating ecological transformation: resist–accept–direct as a path to a new resource management paradigm. BioScience. 2022;72(1): 16–29. doi: 10.1093/biosci/biab067
57. Dale L. Climate change adaptation: an earth institute sustainability primer. New York: Columbia University Press; 2022.
58. Rondeau RJ, Austin G, Miller RS, Parker S, Breibart A, Conner S, et al. Restoration of wet meadows to enhance Gunnison sage-grouse habitat and drought resilience in arid rangelands. Restor Ecol. 2024;32(2):e14039. doi: 10.1111/ rec.14039
59. Wheaton JM, Bennett SN, Bouwes N, Maestas JD, Shahverdian SM, eds. Low-tech process-based restoration of riverscapes: design manual. Version 1.0. Logan (UT): Utah State University Restoration Consortium; 2019 [cited 2024 Nov 2]. Available from:https://www.wlfw.org/wp-content/ uploads/2023/02/PocketGuide_PDF.pdf
60. Corday J. Restoring western headwater streams with low-tech process-based methods: a review of the science and case study results, challenges, and opportunities. 2024 [cited 2024 Aug 29]. Available from: https://www.americanrivers. org/wp-content/uploads/2024/02/LTPBR-Science-Report-Version-2.0-Jan2024_FINAL3-SHARE.pdf
61. Goldfarb B. Eager: the surprising, secret life of beavers and why they matter. White River Junction (VT): Chelsea Green Publishing; 2018.

62. Brazier RE, Puttock A, Graham HA, Auster RE, Davies KH, Brown CM. Beaver: nature's ecosystem engineers. WIREs Water. 2021;8(1):e1494. doi: 10.1002/wat2.1494

63. Norman LM, Lal R, Wohl E, Fairfax E, Gellis AC, Pollock MM. Natural infrastructure in dryland streams (NIDS) can establish regenerative wetland sinks that reverse desertification and strengthen climate resilience. Sci Total Environ. 2022;849: 157738. doi: 10.1016/j.scitotenv.2022.157738

64. Wohl E. Resilience in river corridors: how much do we need? Perspect Earth Space Sci. 2024;5(1):e2023CN000226. doi: 10.1029/2023CN000226

65. Conlisk E, Chamberlin L, Vernon M, Dybala KE. Evidence for the multiple benefits of wetland conservation in North America: carbon, biodiversity, and beyond. Point Blue, March; 2023 [cited 2024 Aug 27]. Available from: http://www.pointblue.org/wp-content/uploads/2023/03/Conlisk-et-al.-2023-Evidence-for-the-Multiple-Benefits-of-Wetland-Conservation-in-North-America-1.pdf

66. Holl KD, Brancalion PH. Tree planting is not a simple solution. Science. 2020;368(6491):580–1. doi: 10.1126/science.aba8232

67. Hudiburg T, Mathias J, Bartowitz K, Berardi DM, Bryant K, Graham E, et al. Terrestrial carbon dynamics in an era of increasing wildfire. Nat Clim Change. 2023;13(12):1306–16. doi: 10.1038/s41558-023-01881-4

68. Kirschbaum MU, Cowie AL, Peñuelas J, Smith P, Conant RT, Sage RF, et al. Is tree planting an effective strategy for climate change mitigation? Sci Total Environ. 2024; 20;909:168479. doi: 10.1016/j.scitotenv.2023.168479

69. Lancaster B. Rainwater harvesting for drylands and beyond. Guiding principles to welcome rain into your life and landscape. Vol. 1. Tucon (AZ): Rainsource Press; 2019.

70. Jensen JK, Alkan Olsson J, von Post M, Isaksson C. Reconnecting children to nature: the efficacy of a wildlife intervention depends on local nature and socio-economic context, but not on urbanisation. People Nat. 2024;6:1987-2000. doi: 10.1002/pan3.10702

71. Maher NM. Nature's new Deal: the civilian conservation corps and the roots of the American environmental movement. New York: Oxford University Press; 2007.

72. Schwartz JD. The reindeer chronicles: and other inspiring stories of working with nature to heal the Earth. White River Junction (VT): Chelsea Green Publishing; 2020.