CONSERVATION

Committing to ecological restoration

Efforts around the globe need legal and policy clarification

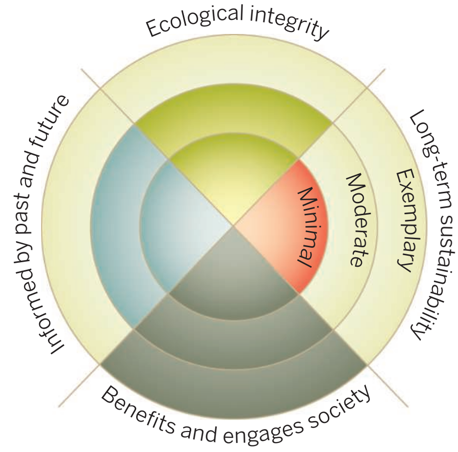
By **Katharine Suding,**[1*] **Eric Higgs,**[2]
Margaret Palmer,[3] **J. Baird Callicott,**[4]
Christopher B. Anderson,[5] **Matthew Baker,**[6] **John J. Gutrich,**[7]
Kelly L. Hondula,[8] **Matthew C. LaFevor,**[8]
Brendon M. H. Larson,[9] **Alan Randall,**[10,11]
J. B. Ruhl,[12] **Katrina Z. S. Schwartz**[13]

At the September 2014 United Nations Climate Summit, governments rallied around an international agreement—the New York Declaration on Forests—that underscored restoration of degraded ecosystems as an auspicious solution to climate change. Ethiopia committed to restore more than one-sixth of its land. Uganda, the Democratic Republic of Congo, Guatemala, and Colombia pledged to restore huge areas within their borders. In total, parties committed to restore a staggering 350 million hectares by 2030.

POLICY

The ambition affirms restoration's growing importance in environmental policy. These new commitments follow the 2010 Aichi Convention on Biological Diversity (to restore at least 15% of degraded ecosystems globally) and the 2011 Bonn Challenge (to restore 150 million hectares). Particularly when accompanied by policies to reduce further losses (as in the New York Declaration), restoration of such magnitude holds promise to address global environmental concerns.

Achieving this promise requires careful thought about how we restore ecosystems (*1*, *2*). We outline four core principles of scientifically based, workable, and comprehensive restoration (*3*) that can provide appropriate best practice guidelines in legal, policy, and planning efforts.



Four principles for planning restoration. The use of four principles identifies trade-offs in the planning process and the extent of departure from the full opportunities presented by comprehensive ecological restoration [example after (*25*)].

There is little question that ecological restoration can provide substantial benefits that enhance quality of life (*4*). A considerable body of science suggests that restoration can guide establishment of complex self-sustaining interactions between biota, biophysical features, and processes that compose an ecosystem (*5*, *6*). The science also emphasizes the challenging nature of the endeavor: Our interventions rarely achieve full recovery, and uncertainty is to be expected in dealing with natural recovery processes (*7*, *8*). Continuing environmental change further challenges the notion of recovery (*9*).

Some have thus questioned whether declarations of intent to restore will in fact result in substantive restoration of degraded land (*10*, *11*). Others have cautioned that these declarations may spur actions that compromise biodiversity: for instance, by replacing ancient grassy biomes with forest plantations (*12*) or by planting species in climatic zones where they may not persist (*13*). Others emphasize that a focus on one specialized goal (e.g., climate change mitigation) might not deliver intended benefits because of complexity in ecosystem dynamics in ways and over time scales not fully understood (*14*, *15*).

Specialized programs such as compensatory mitigation, endangered species conservation, and ecosystem service delivery can be a useful contribution to—but are not synonymous with—ecological restoration (*16*, *17*). Such distinctions are not trivial because projects undertaken in the name of restoration may in fact be something different and, in many cases, have been demonstrated to achieve neither restoration nor their intended purposes (*17*, *18*). Delivery of diverse benefits will depend on how on-the-ground efforts are conceived and implemented (*7*, *8*). Avoiding mistakes on a grand scale requires clear practice principles (*10*).

FOUR PRINCIPLES. We advocate considering four principles when planning restoration. The degree to which each principle is achievable will vary on the basis of social and ecological context. By taking into account these comprehensive principles, trade-offs inherent in specialized projects are avoided, which increases the prospect of sustainable and valuable overall outcomes (see the figure).

1. Restoration increases ecological integrity. Restoration initiates or accelerates recovery of degraded areas by prioritizing the complexity of biological assemblages, including species composition and representation of all functional groups, as well as the features and processes needed to sustain these biota and to support ecosystem function (*3*, *4*).

2. Restoration is sustainable in the long term. Restoration aims to establish systems that are self-sustaining and resilient; thus, they must be consistent with their environmental context and landscape setting. Once a restoration project is complete, the goal should be to minimize human intervention over the long term. When intervention is required, it should be to simulate natural processes that the landscape no longer provides (e.g., fire or invasive species removal) or to support traditional practices of local communities (*8*, *9*).

3. Restoration is informed by the past and future. Historical knowledge, in its many forms, can indicate how ecosystems functioned in the past and can provide references for identifying potential future trajectories and measuring functional and compositional success of projects (*19*). However, the unprecedented pace and spatial extent of anthropogenic changes in the present era can create conditions that depart strongly from historical trends (*9*). Often, then, history serves less as a template and more as a guide for determining appropriate restoration goals (*19*, *20*).

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[1] University of Colorado Boulder, Boulder, CO 80309, USA. [2] University of Victoria, Victoria, British Columbia V8W 2Y2, Canada. [3] University of Maryland, College Park, MD 20742, USA. [4] University of North Texas, Denton, TX 76203, USA. [5] Consejo Nacional de Investigaciones Científicas y Técnicas and National University of Tierra del Fuego, Ushuaia, TDF 9410, Argentina. [6] University of Maryland Baltimore County, Baltimore, MD 21250, USA. [7] Southern Oregon University, Ashland, OR 97520, USA. [8] National Socio-Environmental Synthesis Center, University of Maryland, Annapolis, MD 21401, USA. [9] University of Waterloo, Waterloo, Ontario N2L 3G1, Canada. [10] Ohio State University, Columbus, OH 43210, USA. [11] University of Sydney, Sydney, New South Wales 2006, Australia. [12] Vanderbilt University Law School, Nashville, TN 37203, USA. [13] Woodrow Wilson International Center for Scholars, Washington, DC 20004, USA.
*Corresponding author. suding@colorado.edu

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4. Restoration benefits and engages society. Restoration focuses on recovering biodiversity and supporting the intrinsic value of nature (*21*). It also provides a suite of ecosystem services (e.g., improved water quality, fertile and stable soils, drought and flood buffering, genetic diversity, and carbon sequestration) that enhance human quality of life (e.g., clean water, food security, enhanced health, and effective governance) (*22*). Restoration engages people through direct participation and, thus, increases understanding of ecosystems and their benefits and strengthens human communities (*4*).

Parties to the U.N. Declaration will consider a variety of ways to achieve the new restoration commitments. We advocate adoption of all four principles as normative standards that assess intent at the planning stage, developed in conjunction with consideration of levels of uncertainty (in both the means and ends), the degree to which each principle could be attained, and legal or regulatory frameworks (*23*). Components that constitute ecological integrity will differ across ecosystems; they will need to be described and made practical through best practice guidelines (*4*). The degree to which restoration can be self-sustaining will depend on landscape context; ongoing interventions may be required in some cases to ensure ecological goals consistent with local context are met (*6*). Flexibility regarding the degree of historical fidelity will be needed to ensure success in rapidly changing environments (*9*). Ethical considerations can supersede direct societal benefits, particularly when ecocentric ideals are followed (*21*).

> ***"Our four principles provide a necessary foundation to achieve sustainability and resilience into the future."***

To achieve new restoration commitments, it will be tempting to consider specialized projects that emphasize one principle rather than attending to the full suite of potential opportunities. Degraded lands could be converted to carbon farms, where monocultures of fast-growing tree species are planted and managed to optimize carbon sequestration (*24*). Green infrastructure could provide vegetation that fixes carbon and increases permeable surfaces (*25*). As valuable as these strategies may be, they alone do not constitute comprehensive ecological restoration. To contribute to our commitment to restore, the scope of these strategies should be broadened to include all restoration principles (see the table).

We urge parties to utilize all principles in their planning and to maintain a broad purpose. Although a comprehensive plan may require a more integrative approach than one aimed toward a specialized purpose, considering all four guiding principles is most consistent with ecological and social science and most likely to realize accepted benefits of restoration without net ecological loss.

Our four principles provide a necessary foundation to achieve sustainability and

Application of guiding principles for restoration

Consideration of a comprehensive set of principles, with each principle situated along a continuum of effectiveness, should be a necessary provision of global restoration efforts.

	Four guiding principles			
EXAMPLES	ECOLOGICAL INTEGRITY	LONG-TERM SUSTAINABILITY	BENEFITS AND ENGAGES SOCIETY	INFORMED BY PAST AND FUTURE
Mitigation Compensatory mitigation for mountaintop mining impacts on streams, Appalachia, USA (*26*)	**Minimal** Project implementation most often based only on physical structure	**Minimal** Ongoing maintenance often required. Large changes in environmental context unaccounted for	**Minimal** Net loss of aquatic resources. Economic value of mining placed above environmental losses	**Minimal** Historical or reference ecosystems evaluated by length or oversimplified stream "units" rather than functional metrics
Ecosystem services Global Partnership on Forest and Landscape Restoration, Pamu Berekum, Ghana (*27*)	**Minimal** Tree-planting focus, with little attention to diversity or other processes and functions. Planting targets in ha/year of plantations	**Moderate** Increased rural livelihoods will decrease probability of unsustainable harvesting	**Exemplary** Increased carbon sequestration and food production. Participatory planning. Better income and rural livelihoods	**Minimal** Most focus on plantation methods, some attention to including valued indigenous tree species
Urban greening Cheonggyecheon stream restoration, Seoul, South Korea (*25*)	**Moderate** Increased biodiversity sixfold, including marsh plants, fish, and birds, but at considerable capital cost given central location in large urban region	**Minimal** To keep river flowing, water must be pumped from Han River and underground reserves at a cost of >200 million yen per year	**Exemplary** Reduced urban heat island effect and small-particle air pollution. Increased property values. Provided critical natural habitat for recreation in urban core	**Moderate** Redirected underground waterways. Historically, an intermittent stream with strong cultural significance
Endangered species El Segundo blue butterfly (*Euphilotes battoides allyni*), California, USA (*28*)	**Moderate** Focus on host plant, coast buckwheat (*Eriogonum parvifolium*)	**Minimal** Habitat protection and conservation	**Moderate** Intrinsic value of species preservation	**Exemplary** Preservation of last remaining coastal dunes in butterfly range
Habitat restoration Postlogging stream restoration, Lyell Island, Gwaii Haanas, Haida Gwaii, British Columbia, Canada (*4*)	**Exemplary** Integrated approach to habitat restoration that focused on several aspects of diversity and function	**Exemplary** Cessation of logging, relative absence of invasive species, cultural engagement, and assisted succession techniques ensure long-term success	**Exemplary** Significant cultural value in recovery of a focal group (salminoid fish), an important food source	**Exemplary** Clear use of intact contemporary reference ecosystems; goals included ecological and cultural continuity

resilience into the future. Ecosystems that are structurally and functionally diverse are more likely to be durable and capable of adapting to future challenges of climate change, introduced species, and land-use change and they can be sustained with a declining investment of human and financial capital over time. Involving people through multiple avenues—from participation to consumption of ecosystem services to cultural renewal—can promote public engagement and stewardship of local ecosystems. Adherence to these principles will add clarity, accountability, and accomplishment in this new era of embracing ecological restoration as an environmental policy tool. ■

REFERENCES AND NOTES

1. N. Shackelford *et al.*, *Restor. Ecol.* **21**, 297 (2013).
2. L. M. Hallett *et al.*, *Restor. Ecol.* **21**, 312 (2013).
3. Science and Policy Working Group, Society for Ecological Restoration, *SER International Primer on Ecological Restoration* (SER, Washington, DC, 2004).
4. K. Keenleyside *et al.*, Eds., *Ecological Restoration for Protected Areas* (International Union for Conservation of Nature, IUCN, Gland, Switzerland, 2012).
5. D. A. Falk, M. A. Palmer, J. B. Zedler, *Foundations of Restoration Ecology* (Island Press, Washington DC, 2007).
6. K. N. Suding, *Annu. Rev. Ecol. Evol. Syst.* **42**, 465 (2011).
7. R. L. Chazdon, *Second Growth: The Promise of Tropical Forest Regeneration in an Age of Deforestation* (Univ. of Chicago Press, Chicago, 2014).
8. E. Higgs, *Nature by Design* (MIT Press, Cambridge, MA, 2003).
9. R. J. Hobbs, L. M. Hallett, P. R. Ehrlich, H. A. Mooney, *Bioscience* **61**, 442 (2011).
10. C. Biron, Inter Press Service, 3 October 2014.
11. M. H. M. Menz, K. W. Dixon, R. J. Hobbs, *Science* **339**, 526 (2013).
12. J. W. Veldman *et al.*, *Science* **347**, 484 (2015).
13. Afforestation in China: Great green wall, *Economist*, 23 August 2014).
14. L. L. Bremer, K. A. Farley, *Biodivers. Conserv.* **19**, 3893 (2010).
15. L. Ciccarese, A. Mattsson, D. Pettenella, *New For.* **43**, 543 (2012).
16. M. A. Palmer, S. Filoso, R. M. Fanelli, *Ecol. Eng.* **65**, 62 (2014).
17. A. Telesetsky, *Vermont J. Environ. Law* **14**, 494 (2013).
18. J. Salzman, J. B. Ruhl, *Stanford Law Rev.* **53**, 607 (2000).
19. E. Higgs *et al.*, *Front. Ecol. Environ.* **12**, 499 (2014).
20. L. Balaguer, A. Escudero, J. F. Martín-Duque, I. Mola, J. Aronson, *Conserv. Biol.* **176**, 12 (2014).
21. J. B. Callicott, *Principles of Conservation Biology* (Sinauer Assoc., Sunderland, MA, 2006)
22. R. S. De Groot *et al.*, *Conserv. Biol.* **27**, 1286 (2013).
23. R. K. Craig, *HELR Harvard Environ. Law Rev.* **34**, 9 (2010).
24. B. B. Lin *et al.*, *Bioscience* **63**, 793 (2013).
25. V. M. Temperton *et al.*, *Restor. Ecol.* **22**, 271 (2014).
26. M. A. Palmer, K. L. Hondula, *Environ. Sci. Technol.* **48**, 10552 (2014).
27. Global Partnership on Forest and Landscape Restoration, Pamu Berekum site; www.forestlandscaperestoration.org/learning-site-pamu-berekum.
28. K. Suckling, N. Greenwald, T. Curry, *On Time, on Target: How the Endangered Species Act Is Saving America's Wildlife* (Center for Biological Diversity, Tucson, AZ, 2012).

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HUMAN GENETICS

GTEx detects genetic effects

The genetic basis for variation among individuals in transcript abundance across tissues is analyzed

By **Greg Gibson**

One of the lessons from the past several years of genomic analysis is that well-conceived, ambitious, and thoughtfully analyzed genetic studies carried out by large consortia can advance the field in giant leaps. They do so both by providing new insight and by generating data sets that are widely accessible to all investigators. It is thus remarkable that, even though we now know that the vast majority of common polymorphisms (variants of a particular DNA sequence) that are associated with disease risk act by modulating gene expression, "big science" transcription analyses have been lacking. This deficit is now addressed with the publication of the first results from the Genotype-Tissue Expression (GTEx) Consortium (*1*), which also includes the findings of Melé *et al.* (*2*) and Rivas *et al.* (*3*), on pages 648, 660, and 666, respectively, in this issue.

GTEx is an effort coordinated by the U.S. National Human Genome Research Institute to understand the genetic basis for variation among individuals in transcript abundance across many tissues (*4*). Hitherto, our knowledge of the genetics of gene expression in humans has derived mostly from studies of blood (*5*), lymphoblast cell lines (*6*), and isolated studies of accessible tissues such as fat or skin (*7*). The plan for GTEx is to associate whole-genome sequence variation with RNA sequencing data for more than 50 tissue types from almost 1000 next-of-kin consented postmortem donors. This knowledge will provide direct evidence addressing the function of the many thousands of disease-associated variants supplied by genome-wide association studies (GWAS) and will illuminate mechanisms of variation for disease risk among healthy people. The pilot phase results (*1*–*3*) are based on data from the first 237 donors, of whom around 100 have RNA samples analyzed in 9 tissues, with data from smaller subsets of donors available for 33 other tissues. The main GTEx Consortium article reports on the genetic regulation of gene expression, whereas Melé *et al.* provide an overview of differences between the "transcriptome"—all RNA molecules, including messenger RNA, ribosomal RNA, transfer RNA, and other long noncoding RNA transcripts—across tissues and individuals. Rivas *et al.* report on the effect that protein-truncating variants have on human transcription, generating a quantitative model of how nonsense-mediated decay (the elimination of transcripts that contain a premature stop codon) varies across tissues and may be genetically regulated.

Previous studies in many organisms have established that common regulatory polymorphisms (expression quantitative trait loci, or cis-eQTLs) located within a few hundred kilobases of a gene significantly influence the expression of at least half of all genes in one tissue or another (*8*). They act locally to influence expression of a nearby gene, and may explain anywhere from a few percent to more than half the variance in abundance of the specific transcript among individuals. These effects are much larger than those typically associated with disease, so the largest eQTL effects can be detected with sample sizes of as few as 100 individuals (*9*). It is to be expected that rare variants also contribute to disease, although their discovery is in its infancy. Epigenetic influences such as chromatin modification and microRNA regulation certainly also explain substantial amounts of the variance. A critical feature of transcriptional variation is the very high degree of co-regulation, sometimes of thousands of genes. This can be attributed to the collective effects of trans-acting regulatory factors (transcription factors, hormones, environmental agents) as well as variation in the abundance of cell types within tissues.

> ***"This knowledge will … illuminate mechanisms of variation for disease risk..."***

One of the major contributions of these first GTEx papers is quantification of the relative contributions of cis-eQTLs in different tissues, suggesting (for example) that thyroid and tibial nerve have twice the number of genes regulated by local polymorphisms than blood or heart (*1*). However, blood seems to have a relatively high level of allele-specific expression (transcription predomi-

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School of Biology, Georgia Institute of Technology, Atlanta, GA 30332, USA. E-mail: greg.gibson@biology.gatech.edu

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