ANNUAL REVIEWS

Annual Review of Environment and Resources

Degradation and Recovery in Changing Forest Landscapes: A Multiscale Conceptual Framework

Jaboury Ghazoul[1,2] and Robin Chazdon[3,4,5]

[1]Ecosystem Management, Department of Environmental Systems Science, ETH Zurich, 8092 Zurich, Switzerland; email: jaboury.ghazoul@env.ethz.ch

[2]Prince Bernhard Chair of International Nature Conservation, Ecology and Biodiversity Group, Utrecht University, 3584 CH Utrecht, The Netherlands

[3]Department of Ecology and Evolutionary Biology, University of Connecticut, Storrs, Connecticut 06269

[4]International Institute for Sustainability, Rio de Janeiro 22460-320, Brazil

[5]Tropical Forests and People Centre, University of the Sunshine Coast, Maroochydore DC, Queensland 4558, Australia

Annu. Rev. Environ. Resour. 2017. 42:161–88

First published online as a Review in Advance on July 27, 2017

The *Annual Review of Environment and Resources* is online at environ.annualreviews.org

https://doi.org/10.1146/annurev-environ-102016-060736

Keywords

alternate stable states, arrested succession, complex adaptive systems, ecological resilience, ecosystem degradation, recovery debt, regeneration, restoration

Abstract

Conceptual confusion revolves around how to define, assess, and overcome land, ecosystem, and landscape degradation. Common elements link degradation and recovery processes, offering ways to advance local, regional, and global initiatives to reduce degradation and promote the recovery of ecosystems and landscapes in forest biomes. Biophysical attributes of degradation and recovery can be measured, but the relevance of selected attributes across scales is subject to values that determine preferred states. Degradation defined in the context of a resilience-based approach is a state where the capacity for regeneration is greatly reduced or lost, recovery is arrested, core interactions and feedbacks are broken, and human intervention is required to initiate a trajectory of recovery. Another approach combines degradation and recovery processes through the concept of recovery debt, the cumulative lost benefits incurred, relative to a target state during phases of degradation and recovery. Degradation and recovery can also be described in terms of societal willingness to invest in improved management or restoration. Interventions can facilitate recovery to new stable or persistent states that provide multiple social and ecological benefits at land, ecosystem, and landscape scales. Multiple trajectories of recovery, as well as historic and ongoing chronic environmental change, might, however, mean that recovery to an original reference state is not possible.

Contents

1. INTRODUCTION

Approximately 25% of global land area is subject to some degree of degradation, encompassing soil erosion, salinization, peatland and wetland drainage, and forest degradation (1). The area of degraded tropical forest alone is estimated to be about 500 million hectares (ha) and could well exceed that of deforestation in the Amazon, the Congo basin, and Indonesia (2). Forest and land degradation directly affect the livelihoods of hundreds of millions of people and particularly afflict people living in poverty in the tropics (3). Environmental degradation is not, however, a new problem. Histories of degradation and landscape transformation extend back thousands of years, as evidenced by archaeological remains and charcoal in soil layers in temperate and tropical regions (4, 5). Problems of soil and vegetation degradation and concepts of ecological health were recognized by Confucius in the east and by Plato and Aristotle in the west. Environmental degradation might even have contributed to catastrophic declines of species (6) and, more controversially, human societies (7, 8). In the modern era, the science of environmental degradation stretches back to the mid-twentieth century with the seminal works of Jacks & Whyte (9), Osborn (10), Leopold (11), and Carson (12). A new generation of environmentally concerned scientists has argued that the impacts of degradation and its consequences for human and environmental well-being are more acute and widespread than ever before, owing to global population pressures and massive scales of resource extraction and land transformation. Degradation applies to soil, land, ecosystems, and landscapes, and it has multiple human and ecological impacts at each scale. Reducing degradation and restoring currently degraded lands are urgently needed actions to improve food production and resource provision, maintain ecosystem services, mitigate climate change, and conserve biodiversity.

The international community and three Rio Conventions have recognized the need to respond to land and forest degradation. In 2007, the Thirteenth Conference of the Parties of the United Nations Framework Convention on Climate Change initiated the Reducing Emissions from Deforestation and Forest Degradation (REDD+) in Developing Countries Programme (**http://www.un-redd.org/**). In 2011, the UN Convention to Combat Desertification proposed a target of achieving land degradation neutrality by 2030 (13). The Aichi Biodiversity Target of the UN Convention on Biological Diversity calls for restoring 15% of degraded lands within member countries (**https://www.cbd.int/doc/strategic-plan/targets/T15-quick-guide-en.pdf**), and a target promoted by the 2011 Bonn Challenge (**http://www.bonnchallenge.org/content/challenge**) would restore 150 million ha of global forest by 2020, extended by the 2014 New York Declaration on Forests to 350 million ha by 2030 (**http://www.greenbeltmovement.org/sites/greenbeltmovement.org/files/Forests%20Declaration%20Text.pdf**).

These targets have invigorated the debate regarding how to define, assess, and respond to degradation of land, forest, and nonforest ecosystems (14, 15). Yet conceptual confusion remains as to how to address these challenges. Disparities in interpreting degradation rest largely on differing perspectives, values, and objectives (16). Degradation is a multidimensional construct, studied by separate disciplinary groups under different conceptual frameworks and thus construed, defined, and assessed in a variety of ways. Definitions matter because they have both practical and policy implications. Although the development of transparent and internationally harmonized forest policies relies on a shared interpretation of degradation, different interpretations of forest degradation are in common usage (17; see the sidebar titled Selected Definitions of Forest Degradation). Even organizations, such as the Food and Agriculture Organization (FAO) of the UN, the International Tropical Timber Organization, the United Nations Environmental Programme (UNEP), and the Intergovernmental Panel on Climate Change (IPCC), which have broadly aligned objectives to reduce carbon emissions from forest degradation, apply different definitions suited to their own purposes (18; see the sidebar titled Selected Definitions of Forest Degradation). Without clear and agreed interpretations, assessments of degradation and recovery can easily be subverted to suit particular agendas. For example, governments deprive people of land-use rights if those people are viewed as agents of land degradation, despite contested interpretations of degradation (19, 20). It is also in many countries' interests to overestimate degradation and deforestation to facilitate delivery of REDD+ targets. Vague or open definitions abet this policy (18, 21). Papua New Guinea, for example, recently reported that half of the country's remaining forests will be lost or damaged by 2021, a claim contested on the basis that it erroneously considered traditional shifting cultivation as a precursor to inevitable degradation (22).

We explore interpretations of degradation and recovery in forested systems. We begin by differentiating alternative interpretations of degradation, namely, changes in structure, composition, function, services, and human perceptions of degradation. We address environmental degradation and recovery at different spatial and hierarchical scales and interpret these processes in the context of resilience concepts embedded within frameworks of complex adaptive systems and alternative stable states (23, 24). We apply the concept of recovery debt (25), the cumulative lost benefits incurred, relative to a target state during phases of degradation and recovery as a way to link these processes and states. Degradation and recovery can also be viewed together in terms of societal willingness to invest in sustainable land management, conservation, or restoration practices. Our review concludes with a discussion of indicators and thresholds of degradation and recovery that can serve as a foundation for operationalizing and applying the conceptual framework presented.

Resilience: rate of return of an ecosystem to an equilibrium state, its ability to withstand change, or combinations of these

Complex adaptive system: a biological community in a social and abiotic environment, interactions across which create feedbacks that drive self-regulating properties

Stable state: an ecosystem condition that maintains its fundamental functions and character in the face of disturbance

Recovery debt: the cumulative loss of selected functions relative to a reference state experienced during the recovery phase

Succession: postdisturbance processes and trajectories of ecological change in compositional and functional attributes toward one or more persistent ecosystem states

2. CONCEPTS OF DEGRADATION AND RECOVERY

Degradation implies a persistent reduction of some attribute relative to a preferred (nondegraded) condition. Recovery is the process of returning to the preferred condition through natural succession or active intervention. Unlike deforestation, which is simply the conversion of forested to nonforested land cover, forest degradation involves changes in the structure, composition, or

SELECTED DEFINITIONS OF FOREST DEGRADATION

Degradation has been variously defined as a state or process in which ecosystem resources or attributes are reduced relative to some reference state or goals owing to human disturbance. Other definitions are framed within the context of alternative stable states or changes in the internal dynamics of an ecosystem, with the implication that the resulting outcomes are not desired. The following are examples of these definitions:

The deterioration of the environment through the depletion of resources, such as air, water, and soil; the destruction of ecosystems; and the extinction of wildlife . . . any change or disturbance to the environment perceived to be deleterious or undesirable (197)

"The reduction of canopy cover and/or stocking of the forest through logging, fire, windfelling or other events, provided that the canopy cover stays above 10% . . . the long-term reduction of the overall supply of benefits from forest, which includes wood, biodiversity and other products or service" (**http://www.fao.org/docrep/009/j9345e/j9345e08.htm**)

"A secondary forest that has lost, through human activities, the structure, function, species composition or productivity normally associated with a natural forest type expected on that site" (**https://www.cbd.int/doc/meetings/sbstta/sbstta-07/information/sbstta-07-inf-03-en.pdf**; p. 139)

"A direct human-induced long-term loss (persisting for X years or more) of at least Y% of forest carbon stocks (and forest values) since time T and not qualifying as deforestation" (198, p. 16)

"A loss of forest structure, productivity, and native species' diversity. A degraded site may still contain trees or forest, but it will have lost its former ecological integrity" (199, p. 23).

The simplification and loss of biodiversity caused by disturbances that are too frequent or severe to allow natural ecosystem recovery. Degradation generally reduces the flow of ecosystem goods and services (200).

The simplification and loss of biodiversity in an ecosystem caused by disturbances . . . including climate change and extreme events, as well as human activities . . . generally reduces flows of ecosystem goods and services (201).

"The incremental and progressive impairment of an ecosystem on account of continuing stress events or punctuated minor disturbances that occur with such frequency that natural recovery does not have time to occur" (202, p. 258)

"A reduction in the capacity of a forest to produce ecosystem services such as carbon storage and wood products as a result of anthropogenic and environmental changes" (45, p. 1)

"The transfer of energy and matter is disrupted in such a way as to shift the balance toward a new equilibrium where the expected outputs are delivered at suboptimal level" (63, p. 8).

"Disturbance becomes degradation . . . when it crosses a threshold beyond the natural resilience of a forest type" (203, p. 4).

Human-induced change forcing the forest past a tipping point that leads to ecosystem change . . . resulting in a loss of services and wood fiber (155)

function of a forest. The outcomes of these changes are subject to alternative interpretations and values, which might be based on productive functions (e.g., goods), biodiversity, carbon storage, or other ecosystem services. The preferred condition might reflect a desire to return to some perceived historical condition, often assumed to be relatively undisturbed by humans. Perceptions of degradation and recovery are, however, social constructs subject to cultural and ethical norms (26, 27). Conflicts among stakeholders can arise. Depending on the historical and ecological benchmarks used, drivers of deforestation and forest degradation, such as increased fire frequency, might be considered beneficial for the rejuvenation and restoration of native grassland ecosystems (14).

A binary interpretation of degradation (i.e., degraded versus not degraded) implies some specified threshold that separates the two states. Although this approach might be amenable to assessment and monitoring, the threshold and the specific attributes considered are often arbitrarily determined and subject to locally relevant contexts or reference points. Different stakeholders, each having particular values and objectives, will have unique perspectives on these issues (17, 28). Thus, degradation can be framed as a process driven by decisions made in the context of socioeconomic conditions, political structures, and biophysical constraints, or as an ecosystem state in which certain valued attributes of the ecosystem are impoverished or lost. This dichotomy loosely reflects the study of environmental degradation by natural and social scientists, the former emphasizing state variables by which degradation is interpreted and the latter focusing on the drivers of degradation. In practice, both approaches are needed to resolve the causes and effects of degradation: A process-based quantitative perspective requires an understanding of both the ecological and social drivers of environmental change.

2.1. Degradation Across Scales

Although we focus on the degradation and recovery of forests, degradation also affects soils and associated agricultural productivity (often referred to as land degradation) as well as other ecosystems encompassing marine, freshwater, and terrestrial biomes. Land, habitat, and ecosystem degradation have never been formally defined and are often used interchangeably (**Figure 1**). Land degradation is usually associated with the state of soils and their productive potential, as well as with land use rather than land cover. Although research has tended to segregate forest and soil degradation, they are, in practice, interlinked processes (29). Vegetation and crop recovery depends on soil fertility (30, 31), whereas changes in tree cover affect nutrient cycling, soil erosion, and landslide risk (32–34).

Habitat degradation refers to the structure and composition of a discrete plant assemblage, although it is difficult to separate such assemblages from the wider ecosystems to which they belong. Ecosystem degradation encompasses not only the structure and composition but also the dynamics and interactions among plants and animals that collectively give rise to a complex adaptive system. Ecosystem degradation therefore implies a loss of dynamics and functional performance resulting from disruption of the community or its interactions.

At the largest scale, landscape degradation refers to changes in the configuration and quality of land-cover patches that affect the flow of species, nutrients, energy, or materials to an extent that disrupts the functioning of ecosystems across the region (**Figure 1**). Degradation at landscape scales encompasses deforestation, forest fragmentation, desertification, and unsustainable land use, which alter landscape composition, connectivity, and watershed functions (**Figure 1**). Indeed, degradation is spatially and temporally heterogeneous, with natural disturbance and recovery overlapping spatially and temporally with anthropogenic degradation and restoration interventions (35). The result is a complex mosaic of variously managed, disturbed, degraded, and recovering patches influenced by historical and current land uses and spatial configurations (31, 36). Consequent changes to landscape connectivity and resource fluxes drive further changes in ecological processes that shape the composition of land units and interactions among them (37, 38). Regeneration processes are affected by the configuration of habitat patches, as are disturbance regimes, such as fire and pathogen outbreaks, or trophic interactions, such as herbivory of seedlings by deer or pollen and seed dispersal (39, 40). Thus degradation, and conversely recovery, in the landscape context recognizes cross-boundary and cross-scale effects on ecological and biogeochemical processes that affect, and are affected by, patch quality and distribution

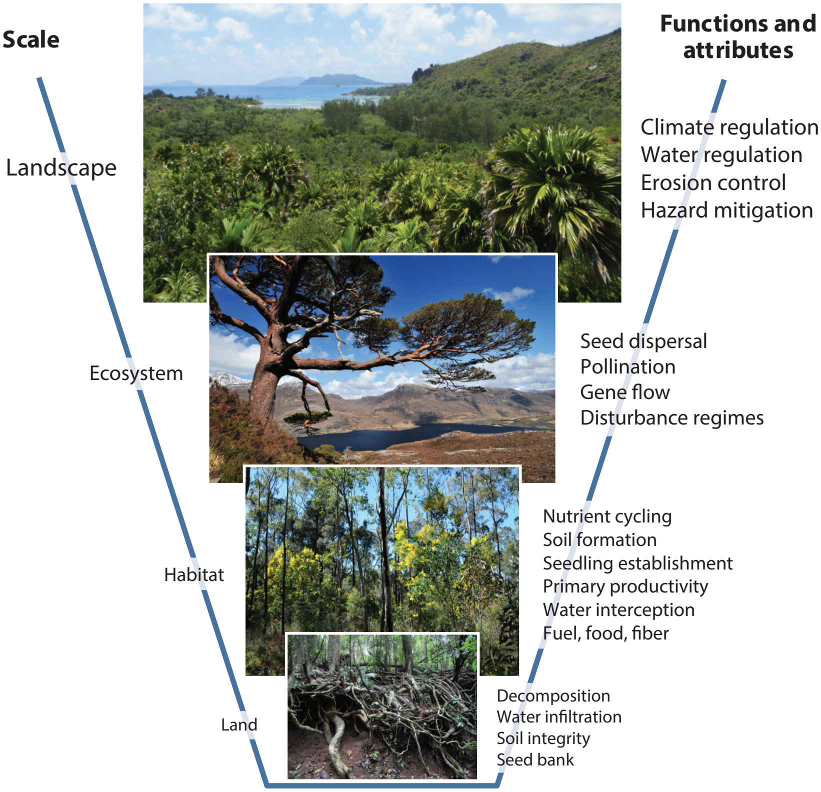


Figure 1

Scales of degradation and recovery, and the functions and attributes potentially affected at each scale. In practice, there are cross-scale effects among these processes, and some attributes might span multiple scales. After McCormick et al. (63).

(**Figure 1**) (41, 42). These feedbacks can alter landscape mosaics gradually and chronically, and occasionally acutely and unexpectedly (38).

2.2. Degradation as a Biophysical Condition

Forest degradation signals a quantitative change in the structure and function of still-forested land. If degradation implies some loss of desired attributes, and recovery implies the return of these attributes, then relevant attributes need to be determined. For global or regional assessments, and for policy initiatives, generic attributes should be agreed upon, but attribute states also need to have relevance for local assessment, governance, and management. A loss of some aspect of ecosystem function, or a loss of biodiversity that underpins many ecosystem functions, is the most widely interpreted indicator of degradation (43). Recently, the loss of ecosystem functions has been framed from a human-centric perspective with an emphasis on the partial or complete loss of goods or ecosystem services (of local, regional, or global relevance) (44, 45). Losses might result from prolonged structural, functional, or biotic changes that diminish the ability of an ecosystem to continue to provide these goods and services. Shortfalls might be initially masked by technical or operational innovations that increase efficiencies and prolong productive capacities. Yet unchecked resource exploitation gradually degrades natural capital, resulting in diminished output when regenerative capacities are exceeded or when unsustainable production of goods and services occurs.

The specification of the time frame used to define degradation, and recovery, is also context dependent. Rates of recovery of timber volume, biomass, hydrological services, biodiversity, or any number of other functions differ widely. Hence, foresters, conservationists, or hydrologists might view degradation and recovery along different temporal scales based on their attributes of interest. Moreover, the time required for recovery of ecosystem properties is strongly linked to the extent of prior ecosystem degradation (25, 46).

Degradation can also be viewed as a state of reduced ecological functionality independent of any utilitarian production function. The composition, dynamics, maintenance, and regeneration of communities and ecosystems are based on ecological processes that include primary productivity and secondary consumption, mutualistic and antagonistic interactions, community assembly, dispersal patterns, and evolutionary change. Landscape structure and composition affect these processes by shaping the regional species pool, providing sources of propagules, and facilitating (or obstructing) material flows.

Defining degradation independently of human-centered utility functions, based on purely biophysical processes, can minimize the influence of value judgments that otherwise clouds definitional clarity but might not necessarily facilitate shared understanding or concern among diverse stakeholders. Thus, biophysical attributes of degradation can be quantified and measured, but the relevance of selected attributes remains subject to values that determine preferred states.

2.3. Social Constructs of Degradation as a Process

Although natural scientists view degradation as an ecosystem state arising from physical processes, social scientists tend to interpret degradation as culturally determined and shaped by norms and processes of human decision making (16, 47). In these cases, degradation results from decisions made as well as from biophysical constraints and vulnerabilities. The human drivers and consequences of degradation (as a process and state) must be understood in the context of specific socioeconomic and political contexts if proximate biophysical drivers limiting recovery are to be overcome. Moreover, management objectives vary across actors, some emphasizing the productive functions of land, whereas others emphasize the biological richness of habitats or the persistence and stability of ecosystems. Even if reduced to a set of quantifiable state attributes, the selection of those attributes is a decision bound to particular objectives and goals.

Perspectives of ecosystem degradation consequently differ across the political-economic dimensions of land use and ecosystem values (16, 48). On the one hand, government officials in Thailand, for example, classify secondary forest as degraded scrubland and attribute the cause of degradation to swidden farming. Swidden farmers, on the other hand, greatly value the nutrients, timber, and nontimber forest products that secondary forest and regenerating fallow provide (19, 49). For these farmers, swidden farming is a way of life that maintains diverse forests in different stages of succession. Moreover, the transition from swidden to other land uses often contributes to permanent deforestation, with the consequent loss of biodiversity, increased weed pressure, declining soil fertility, and accelerated soil erosion (50).

Community-managed agricultural land, swidden fallows, abandoned pasture, second-growth forests, and logged forests are often viewed as abandoned, or otherwise degraded land by governments and companies that seek to establish, for example, deforestation-free oil palm plantations (51, 52). Forests that have been selectively logged and penetrated by logging roads are undervalued for their biodiversity and ecosystem services, and consequently, they become easy targets for conversion to agriculture that has greater short-term value than standing degraded forests (53). In

Rehabilitation: intervention to recover selected aspects of ecosystem functionality without necessarily seeking to recover all ecosystem attributes that formerly existed

Reference state: a conception of a prior state against which a recovering ecosystem is compared and to which restoration activities aspire

the Brazilian state of Pará, government and producers envision an expansion of up to 3,300 km^2 of palm oil plantations on areas designated as abandoned pastures by Brazil's TerraClass project (52), yet many of these areas include young second-growth forests, which are not legally protected from clearing as deforestation applies only to removal of late successional or mature forests.

Perceptions of degradation also apply to productive functions of ecosystems, which shift over time in response to markets and other drivers. In the Scottish Highlands, extensive sheep grazing interests in the early nineteenth century removed people from the land in favor of large-scale consolidated grazing lands. Following collapsing wool prices in the face of international competition, the land was interpreted as overgrazed and degraded, and it was turned over to deer stalking. In the twentieth century, a strategically driven imperative for commercial tree plantations reinterpreted degradation as excessively high densities of deer that prevent forest establishment. Land degradation is now in the process of being reinterpreted once more as social and political winds shift in favor of restoring native tree cover (47, 54). Changing societal demands and, indeed, an environmental reawakening of society have led to the reinvention of the environment itself as wild land for recreation and tourism and as a haven for biodiversity.

Landscapes with long histories of human transformation are frequently valued as cultural landscapes embedded within the historical traditions of a people. Changes in traditional land management practices might be conceived as a form of degradation even when this leads to the recovery of seminatural ecosystems (55, 56). Such concepts owe more to sociocultural perspectives than to specific ecological attributes (57, 58). The regeneration of natural elements in abandoned landscapes need not imply a return to past conditions (if these are even known), as future ecosystems might well include exotic species, communities, or disturbance regimes. Concepts of degradation are thus contested between those who favor a return to natural forested conditions and those who wish to preserve cultural landscapes (47).

In view of the need for broad societal support for restoration action, the concepts of degradation and restoration have value as boundary objects, a term that facilitates interdisciplinary discussion through a shared vocabulary even while the understanding of specific meanings differ among parties (59). Using degradation as a boundary object allows natural and social scientists to engage with local stakeholders and policy makers while avoiding barriers to shared understanding created by more specific interpretations of the concept (60, 61). Boundary objects do, however, come at a cost of reduced clarity and transparency, although such attributes can be attractive to policy makers (61, 62), and decisions made on this basis might have unexpected outcomes for some parties. Discrepancies can therefore arise between political and operational definitions of degradation. A recent example is the 2008 EU Renewable Energy Directive greenhouse gas bonus for biofuel feedstock produced on "severely degraded or contaminated lands," which remains unclaimed as the working definition is not technically or operationally applicable (63). The intentional framing in policy discourses of degradation and degraded land in broad and inclusive terms does not lead to targeted and effective action (63). Similarly vague definitions and terminology surround policies and interventions aimed at forest recovery, which can include rehabilitation, recuperation, reforestation, regeneration, or restoration (62).

2.4. Degradation as Recovery Debt

Degradation and recovery are mostly treated separately as a state and process, respectively. Yet a severely disturbed state might be considered less degraded if it is quickly able to recover to the reference state. Combining the extent of disturbance (as a state) with the process of recovery offers a means by which degradation and recovery can be combined as recovery debt, the cumulative loss of selected functions relative to a reference state experienced during the recovery phase (25)

(**Figure 2*a***). Degradation can thus be framed as a continuous recovery debt function that is a product of both the degree of disturbance and the rate and trajectory of recovery (**Figure 2*a***).

Recovery debt is effectively the cost of lost ecosystem functions, services, biodiversity, or other attributes over time. The rate and trajectory of recovery can describe outcomes in terms of current, future, and cumulative costs for a variety of recovery scenarios (**Figure 2*a***). Such costs can be represented financially and can be calibrated over time, which could facilitate cost-benefit analyses for different types of restoration interventions. Spatially explicit cost-benefit analyses could help optimize and map the most cost-effective areas for restoration (64, 65) and also minimize risks of displacing forest-degrading activities elsewhere (66, 67). The recovery debt concept also accommodates the quantification of costs of chronic degradation or transformation to alternative stable states (**Figure 2*b***). Indeed, recovery debt begins to accumulate during the degradation phase, which can be a gradual process unfolding over years or decades and might eventually begin to recover or alternatively move the system to a new stable state (**Figure 2*b***).

Active restoration: intervention to promote the recovery of a habitat, ecosystem, or landscape that has been degraded or damaged

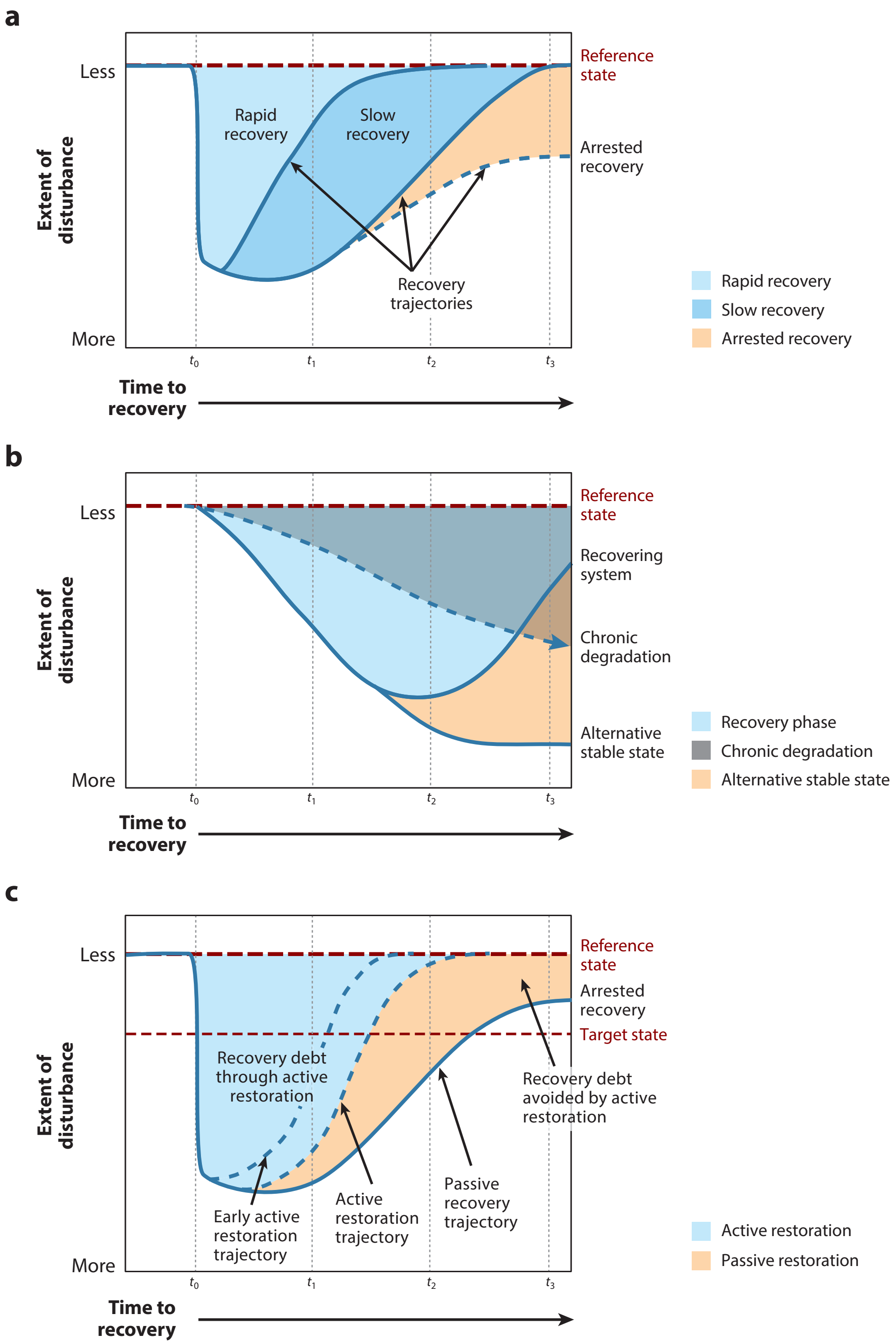
Passive restoration: intentional nonintervention to allow ecosystem recovery through natural regenerative processes

Active restoration intervention aims to accelerate recovery to a target or reference state (**Figure 2*c***). To be economically attractive, the avoided recovery debt resulting from restoration interventions should exceed the cost of these interventions. Early restoration action, if successful, should minimize recovery debts (**Figure 2*c***), although the costs of early restoration might be greater as recovery is often dependent on initial conditions. Moreover, even though some restoration interventions may initially accelerate recovery, later recovery processes can be constrained. The early acceleration of forest recovery by planting Andean alder, *Alnus acuminata*, for example, can lead to impeded recovery of biodiversity 30 years later as compared to naturally regenerating secondary forests in the same area (68). The decision as to whether to invest in active restoration might also depend on the target objective. Should this objective lie short of full recovery (the target state in **Figure 2*c***) the lower additional debt attributable to passive recovery might not exceed the cost of active restoration, making active restoration less cost effective. Similarly, if disturbance to the ecosystem is relatively light, then passive restoration might be sufficient to allow for rapid recovery without incurring costly interventions. Many forests classified as degraded around the world are regenerating naturally without human intervention (31, 69).

2.5. Coupling Biophysical and Societal Values

Degradation and recovery can also be viewed together in terms of societal willingness to invest in sustainable land management or conservation and restoration practices (**Figure 3**), which can be informed by calculations of recovery debt. Willingness to invest in conservation is expected to be highest for undisturbed landscapes or ecosystems but to gradually decline as these systems are increasingly developed for infrastructure, mining, agriculture, and other interests, in line with decreasing conservation value. As the benefits of exploitative extraction or development are increasingly realized and profits are prioritized, societal willingness to conserve or restore land declines. This trend is reflected in the expansion of the logging frontier in South America and in the expansion of oil palm development in Southeast Asia. Gradually, either through increasing environmental concern or diminishing returns, societal interest in improving environmental management rises, which if successful improves environmental sustainability. In Minas Gerais State in Brazil, for example, coffee smallholders are reconciling sustainable agriculture, livelihood improvements, and biodiversity conservation by adopting more diverse agroforestry, which makes greater use of native trees to restore soil fertility while eliminating exotic tree species (70).

Should the state of the environment continue to decline, willingness to invest in restoration or other sustainability-related activities rises in response to the loss of production benefits from increasingly impoverished land. This is increasingly reflected in policies and incentives, as well as in


a
Less
More
Extent of disturbance
Rapid recovery
Slow recovery
Recovery trajectories
Reference state
Arrested recovery
t_0
t_1
t_2
t_3
Time to recovery
Rapid recovery
Slow recovery
Arrested recovery
b
Less
More
Extent of disturbance
Reference state
Recovering system
Chronic degradation
Alternative stable state
t_0
t_1
t_2
t_3
Time to recovery
Recovery phase
Chronic degradation
Alternative stable state
c
Less
More
Extent of disturbance
Reference state
Arrested recovery
Target state
Recovery debt through active restoration
Recovery debt avoided by active restoration
Early active restoration trajectory
Active restoration trajectory
Passive recovery trajectory
t_0
t_1
t_2
t_3
Time to recovery
Active restoration
Passive restoration

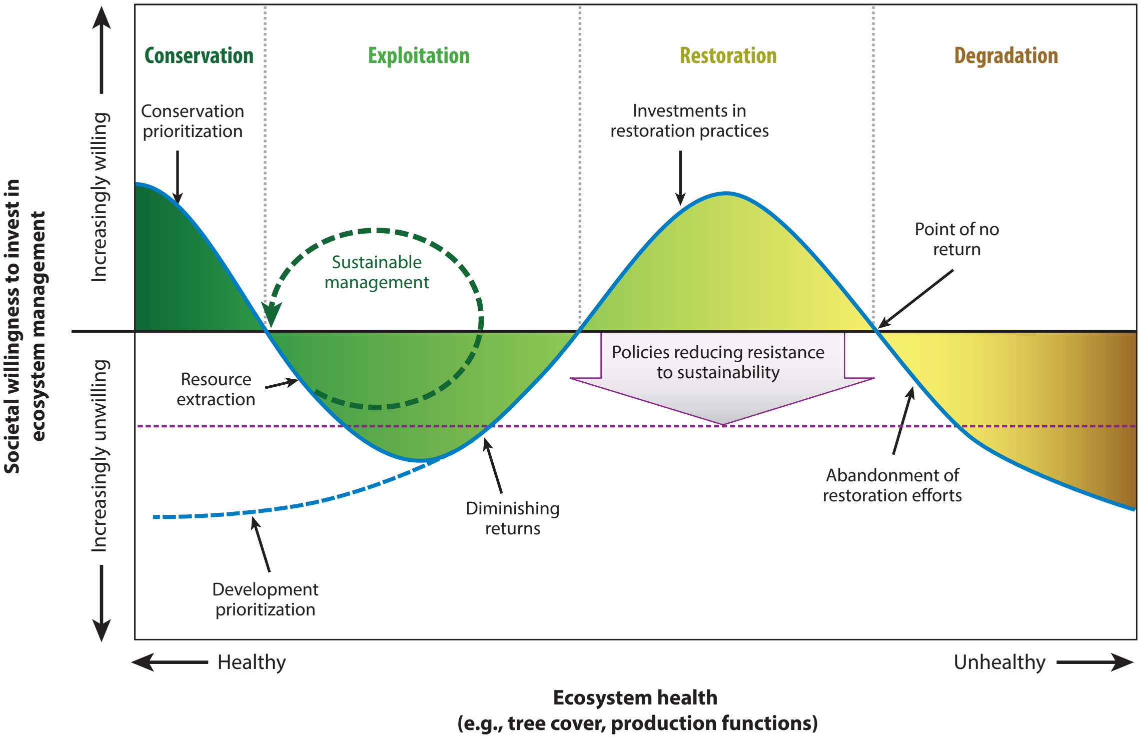


Figure 3

Stages of environmental degradation and recovery expressed in terms of societal willingness to invest in ecosystem management. Willingness to invest in preserving relatively undisturbed landscapes is greater on account of high conservation values but declines with increasing exploitation and profit realization. Diminishing returns might increase willingness to invest in sustainable management, but otherwise ecosystem health continues to decline. Continued ecosystem decline might begin to increase environmental concern, reflected by enhanced societal willingness to invest in restoration or rehabilitation activities. Should investments still prove insufficient, continued impoverishment of land might reach a point at which costs of restoration exceed perceived benefits. Beyond this point, the ecosystem might be said to be degraded in that not only have the biophysical values of the ecosystem been reduced, but also societal willingness to recover these values has been lost.

←

Figure 2

Degradation as recovery debt (25), defined as the cumulative reduction of beneficial functions over the course of degradation and subsequent recovery relative to a reference or target state. (*a*) Shaded areas represent recovery debt under scenarios of rapid recovery (*light blue*); slower recovery (*dark blue*), which also encompasses the rapid recovery debt; and arrested recovery (*orange*), which incurs an open-ended recovery debt. (*b*) Recovery debt accumulates during prolonged degradation and at a diminishing rate in the recovery phase (*light blue*); but under chronic degradation recovery, debt continues to increase over time (*gray*); whereas a disturbance leading to an alternative stable state incurs open-ended, cumulative, and substantial recovery debt (*orange*). (*c*) Active restoration can reduce recovery debt relative to passive restoration by accelerating recovery to the target state, with early active restoration action reducing recovery debt further still. Less ambitious target objectives change the passive to active recovery debt ratio and hence the net benefit of active restoration.

rising investments to better manage, restore, or rehabilitate land (71, 72). If restoration investments prove insufficient or unsuccessful, land impoverishment continues, and societal willingness to recover the functions and environmental qualities of the land (at ever increasing costs) begins to fall. Societal willingness to invest in restoration declines to zero when the costs are perceived to outweigh the benefits (the point of no recovery in **Figure 3**), a threshold at which active restoration is either impossible or too costly (73). Environmental states beyond this point might be said to be truly degraded as not only have the functional attributes and environmental benefits of the land been greatly reduced, but societal willingness to invest in restoration is also likely to have been lost.

Policy responses, through incentives and legal instruments, might aim to increase societal willingness to invest in environmental restoration (**Figure 3**). Yet if societal acceptance of restoration actions is itself a function of local or regional environmental conditions, as proposed by **Figure 3**, then restoration policy is likely to have more resonance for some environmental conditions than others. This is based on the perceived benefits of restoration relative to those of development, the initial restoration investments that need to be made, and the probability and proximity of success. In this respect, the concept of recovery debt and its derived costs and benefits can be useful (**Figure 2**). This issue has yet to be formally explored, although cost-benefit analyses of restoration schemes across a range of environmental conditions could provide some indication of societal willingness to invest in restoration. The net benefits of landscape-scale restoration have been found to vary according to existing land-cover and land-use patterns in four regions of Latin America (74), suggesting that acceptance of restoration investments will likewise vary. At regional scales, the net present value of restoration has been projected to be very considerable (75), but the costs of restoration projects, particularly through tree planting, can exceed the ecosystem service monetary benefits at more local scales (74, 76). In each of these cases, the net benefits are likely to be conditional on the initial state of the environment, and hence societal acceptance of restoration interventions could vary accordingly, as implied by **Figure 3**. Moreover, although science might provide evidence supporting the value of restoration interventions, societal acceptance of these actions often lags behind. Thus, social aversion to fire risk remains a barrier to restoring natural fire regimes in fire-dependent forest ecosystems (77–79). Fostering restoration of degraded lands therefore requires an understanding of the feedbacks between ecosystem states, economic returns, and societal perceptions.

3. THE DYNAMICS OF DEGRADATION AND RECOVERY

Viewing forests (and other ecosystems) as complex adaptive systems, consisting of many interacting components across multiple spatial and temporal scales (23, 24), challenges a static binary concept of degradation. Cross-scale interactions drive negative and positive feedbacks that give rise to heterogeneous structures, emergent properties, and linear and nonlinear dynamics. These dynamics provide self-renewing adaptive responses to endogenous and exogenous perturbations, but these responses might follow any number of pathways subject to initial states and interactions among ecosystem variables at various scales. In young regenerating fallows in the central Amazon, for example, recovery of forest structure was most strongly influenced by prior management intensity at stand scales, whereas species diversity was largely determined by landscape configuration (80). In the grassland steppe of Inner Mongolia, degradation is driven by a combination of natural and socioeconomic factors, including continuous drought and overgrazing (81). Similarly, recovery of ecosystems and landscapes requires the alignment of multiple socioeconomic and biophysical enabling factors (82). Managing complex ecosystems is therefore a multidimensional challenge due not only to conflicting human uses and values but also to their inherent complexity and dynamism. Recovery need not return an ecosystem to the original state before degradation, which might not even be possible. Instead, restoration management might aim to facilitate recovery to new alternate desirable states that provide multiple social and ecological benefits at land, ecosystem, and landscape scales.

3.1. Functional Approaches to Restoration

Restoration objectives are increasingly framed within the context of complex ecosystems that express contingent and stochastic dynamics. Precise forest restoration targets are therefore rarely realistic, especially in environmental futures that have no recent analogs (83). Alternate trajectories driven by process-based dynamics responding to changing environmental conditions are more realistic outcomes of restoration interventions (84). Emphasis is shifting from particular end target states toward enhancing the resilience of restored ecosystems, with resilience being the capacity to either resist disturbance or to rapidly reorganize and recover from disturbance while maintaining ecosystem structure and function through time (85, 86). Forests in dry climatic zones, for example, are particularly sensitive to logging or fragmentation, as reduced tree cover can drive positive feedbacks by favoring grasses that increase fire frequencies (87). By contrast, the predominance of wind-dispersed tree species in dry forests implies more rapid recovery than in wet forests, where the majority of species depend on animals for seed dispersal (88, 89). Determining the thresholds at which positive feedbacks begin to drive rapid change, and the set of functional processes required to resist such change and promote recovery, remains challenging (90). Synergistic interactions between natural conditions and human actions are creating novel disturbance regimes that challenge the adaptability and resilience of many forest ecosystems and landscapes. Logged tropical rain forests, for example, are particularly vulnerable to El Niño droughts, the frequency and intensity of which might be linked to climate change, and the resulting tree mortality creates favorable conditions for further forest degradation by human-initiated fires (91, 92).

Theoretical studies suggest that functional diversity underpins resilience at multiple scales (93–95). Ecosystem resilience might be enhanced by two aspects of functional diversity: (*a*) functional redundancy, the variety of species contributing to a particular ecosystem function or functional group, and (*b*) response diversity, the range of responses to disturbances by functionally similar species (93). Although field-based studies indicate a loss of functional redundancy in degraded systems (96, 97), it is more difficult to empirically associate this loss with declining resilience (see 98). Nonetheless, rapid ecosystem recovery often depends on the (re)establishment of functional interactions among species including, for example, plant-soil interactions underlying carbon and nutrient cycling (29, 99), predator control of trophic networks (100, 101), or pollination and seed dispersal (102, 103). A mechanistic understanding of how functional diversity corresponds to biodiversity, ecosystem function, and resilience in recovering ecosystems remains limited (104, 105) and is perhaps even conceptually flawed (106), particularly as functionally important species and interactions might be a necessary but not sufficient condition for recovery (107).

Landscape heterogeneity also shapes functional processes that are mediated by the flow of species or matter across the landscape, including seed dispersal (108), trophic cascades, and pest outbreaks, which in turn affect ecosystem resilience (109) and forest multifunctionality (110). The fine-scale mosaic of trees and open areas that characterize near natural dry conifer woodlands in western North America, for example, provides resilience from frequent fires and pest outbreaks as a result of the emergent properties of the heterogeneous landscape pattern (95). Human land use and forest management based on fire suppression have historically contributed to the homogenization of forested landscapes (111, 112), which might thus be viewed as a landscape-scale indicator of degradation. Conversely, forest management decisions in response to wildfire can contribute, intentionally or otherwise, to heterogeneity of forest conditions at landscape scales (113, 114), which can enhance ecosystem recovery and resilience (114–116).

Loss of heterogeneity can limit response trajectories by constraining forest dynamics (117, 118). Invasive species or disturbance-tolerant native species, for example, tend to homogenize forest environments by reducing local diversity and community turnover (119, 120). Thus, the amount of spatial heterogeneity in forest structure and distribution might itself be interpreted as a degradation metric relevant to landscape scales and readily evaluated using remote sensing technologies. The rapid development of more sophisticated and low-cost remote sensing capabilities is providing opportunities to evaluate landscape and stand heterogeneity in plant form and function (121), the richness of which could enhance ecosystem recovery through functional redundancy and response diversity (122).

3.2. The Utility and Futility of Reference States

Natural reference states, represented by ecosystems in some kind of equilibrium state unaffected by humans, are for the most part idealized constructions without a historical counterpart. Climate change, nitrogen deposition, and biotic mixing now influence ecosystems across the planet, ensuring that historical reference states are neither appropriate nor attainable in coming decades (123, 124). Future forests are likely to be compositionally, functionally, and structurally novel, reducing the relevance of past reference states and confounding concepts of ecosystem degradation (17, 125, 126). Secondary forests are increasingly composed of species combinations and interactions never before realized on account of introduced and invasive species and novel environmental conditions and disturbance regimes. Human disturbance legacies are persistent and continue to shape ecosystem responses well beyond our ability to identify the sources of disturbances (5, 127, 128). Legacies of ancient land use on species composition are found throughout the Neotropics (129, 130). Centuries of clearing, burning, and hunting might change the species pool to one largely dominated by tolerant or adaptable species. In central Africa, for example, long histories of resource use appear to have favored species tolerant to human disturbances, which could explain relatively rapid postlogging forest recovery (131).

Management responses to novel ecosystems range from resisting and reversing their development to tolerating or actively managing them for functionally favorable outcomes (132). In the future, degradation might make little sense other than as a narrowly constructed interpretation based on locally contextualized functions or services. The new forests might nevertheless continue to provide many ecosystem functions, including soil protection, nutrient cycling, carbon storage, and hydrological services (17, 133). In terms of biodiversity conservation, these novel ecosystems might be deemed degraded, but the impossibility of their restoration to prior conditions renders the term moot, particularly if they continue to provide valuable ecosystem services.

In view of increasingly blurred distinctions between natural and anthropogenic disturbances, and between natural and novel ecosystems, interpretations of degradation might more usefully refer to responses to change (i.e., resilience) rather than the attainment of specific reference states (85). Interpreting degradation as the loss of ecological feedbacks that regulate ecosystem dynamics, through flows of energy and matter and associated renewal processes, offers an escape from definitions tied to particular structural and compositional constellations and an opportunity to reorientate novel systems toward more functional ecosystems (132). This perspective requires that environmental managers abandon the goal of returning to past reference states in favor of accepting a wider array of ecosystem states based predominantly on their functionality and renewal processes (83–85). These traits lend adaptability to ecosystems while maintaining beneficial service provision. Such an approach departs from the traditional objectives of conservation focused on maintaining the historical continuity of species and habitat compositions (17).

Relatively undisturbed reference systems might still have relevance when seeking to understand factors and processes that contribute to ecosystem resilience. Nearly natural systems that have persisted for centuries as dynamic self-organizing ecosystems can teach us much about attributes underlying their resilience. Wildfire, for example, is a natural feature of many forested systems that has often been suppressed by human management, which has reduced structural and compositional complexity and increased landscape homogenization (134). An understanding of how natural wildfires structure forested landscapes provides insights as to how degraded forests might be restored using prescribed burning (135–137).

3.3. Multiple Persistent States and Arrested Succession

Natural dynamics encompass multiple stable ecosystem states that collectively comprise the natural forest domain (86). The dynamics inherent in natural systems makes it difficult to recognize a single equilibrium end point of ecosystem recovery. Rather, degradation and recovery should be assessed with respect to a set of persistent ecosystem states that together describe a recognized ecosystem domain (138). The cold temperate forests of northeastern United States, for example, contain stands of birch, white pine, or mixed maple and hemlock, depending on fire frequency and severity. Each of these states is stable given certain fire return intervals, but if fire frequency declines, birch forests gradually shift toward pine and then to maple or hemlock (139). None of these states is degraded, as all are natural states maintained by natural fire regimes of the North American cold temperate forest domain. States that lie outside this domain are qualitatively different in their structure, composition, and dynamics, and are maintained as such by other self-regulating feedbacks (140, 141). Identifying degradation as an ecosystem state independently of short- and long-term natural dynamics can therefore lead to incorrect inferences about the ecosystem's present and future condition (28).

Successional trajectories can be subject to delays, pauses, reversals, and idiosyncrasies, which are shaped by the disturbance regime, interactions among individual disturbance events, legacy effects, spatial configuration of landscape elements, patterns of species or propagule dispersal, competitive and facilitative interactions, local environmental conditions, and chance events (141, 142). Over three decades of observations at Lady Park Wood in Wales, for example, beech (*Fagus*) and birch (*Betula*) forest has transitioned to forest dominated by ash (*Fraxinus*) and lime (*Tilia*) due to an unpredictable combination of severe summer drought in 1976, late April snowfall in 1981, and an exceptional vole outbreak in 1985 (143). Low predictability of successional trajectories coupled with multiple possible outcomes challenge the notion of directional progression toward an equilibrium state (144, 145). Anthropogenically modified environments that include novel species mixes, climates, and disturbance regimes do not fit neatly within current successional theory. Integrating the concept of degradation within the frame of resilience also runs up against the need to account for historical management that affects subsequent processes and patterns of recovery (146). Forest recovery on more intensively managed agricultural sites in the Amazon basin, for example, proceeds at much slower rates than on former swidden cultivation sites (147).

Ecosystem recovery can therefore follow any one of several pathways (148, 149). Postdisturbance biological legacies determine initial conditions that substantially influence trajectories and rates of recovery (142). Subsequent interactions and processes are not only contingent on such legacies but are also influenced by stochastic events including further disturbances. Renewed or severe disturbances might remove biological legacies, reduce ecological memory, and set

Arrested succession: an ecosystem state in which successional dynamics are halted such that continued recovery is not possible without human intervention

Persistent state: a temporarily stable ecosystem over discrete spatial scales, which shifts to alternative states subject to natural dynamics and disturbances

succession on a new course (150). In the Amazon, for example, succession on former pasture lands subject to repeated burning leads to *Vismia*-dominated stands that persist for decades, whereas former cultivated land with little or no burning shows more diverse successional trajectories (80, 151). The arrested succession that characterizes *Vismia* stands is due not only to past management practices that eliminated biological legacies (repeated burning having destroyed the seed bank and the seedlings of most species) but is also due to positive feedbacks created by the ability of *Vismia* to suppress competitor seedling growth (80, 151). Similarly, high liana densities in heavily logged forest compete for light, water, and nutrients, which constrains succession (152). In more extreme cases, heavily degraded and burned forests in the Philippines can become replaced by *Imperata cylindrica* grasslands, which on account of their flammability and competitive characteristics prevent establishment of woody vegetation (153). Similar processes unfold in nonforest ecosystems. Prairie barrens or savannahs, impoverished through the disruption of natural fire regimes, might not recover after the reinstatement of fire if woody vegetation establishes in the intervening period (14, 154).

A highly resilient ecosystem state need not imply that ecosystem attributes are favorable. Indeed, degradation might be characterized as an unfavorable ecosystem state that has high resilience to change and is constrained by positive feedbacks and a limited range of interactions that halt successional processes and reduce natural steady-state dynamics (28, 155). This state might manifest as extremely slow system dynamics or a state of arrested succession stemming from resistance to external perturbations or invasions. These conditions essentially establish a new locally persistent state within the forest domain (28). However, a highly disturbed state is not degraded if it retains the biological legacies and ecological processes that lead to regeneration and succession, even if these regenerative processes are slow. A state can be viewed as degraded if it falls into a condition of arrested succession, at least within meaningful time frames, within its own stability subdomain (28). A degraded system might therefore be described as an unfavorable alternate persistent state with high localized resilience, where a return to its prior ecosystem dynamics or recognizable successional trajectories is not possible (or even likely) by natural processes. Recovery requires human intervention through appropriate restoration or rehabilitation approaches.

In seeking to understand degradation as arrested succession, it is perhaps easier to explore the parameters that underpin the recovery of forest ecosystems. Lugo et al. (156) identified six such parameters or state variables: accumulation of belowground nutrients; rapid fluxes of nutrients, biomass, and populations; biotic control of ecosystem functions; species richness and functional redundancy; negative feedbacks; and, lastly, high species turnover. Ecological memory (or biological legacies) and critical mutualisms should also be included (157). Degradation can thus be interpreted and quantified in terms of the limited functioning or loss of these processes and the consequent limited change in state variables. Indicators of degradation might include soil erosion or loss of key nutrients, perhaps owing to a shortening of fallow periods (147, 158), reduced rates of nutrient mobilization, or declines in biological interactions that underlie regenerative functions. Defaunation resulting in the loss of dispersal function can reduce regeneration capacity, especially for large-seeded tree species (159, 160). Climate change is an increasingly important factor influencing forest recovery processes (161). Forests in dry regions are particularly vulnerable to resilience loss due to positive feedbacks that maintain alternate vegetation states during extreme droughts (162).

Regeneration processes operate at different rates in different systems, and consequently some forests recover from disturbance more quickly than others. Dry forests initially recover biomass rapidly on account of resprouting and abundant wind-dispersed recruitment, whereas moist forests accumulate biomass more rapidly than dry forests at later successional stages on account of faster growth rates and larger tree sizes (163). Both forest types do eventually recover, so on the basis of degradation as arrested succession, neither forest type is degraded so long as recovery is proceeding. In practice, very slow recovery may be difficult to detect and is thus interpreted as no recovery, which is subject to the metrics used and the duration and precision of measurement. This interpretation of degradation makes no inference about the direction of ecosystem change and accepts that trajectories might be complex and do not necessarily follow smooth linear pathways to an original state (141). Arrested ecosystem dynamics can also be an indicator of landscape degradation where ecological memory is reduced to the point that native ecosystems can no longer regenerate or support native biodiversity (164) as might occur in shifting cultivation landscapes where a tipping point of agricultural pressure is associated with a loss of forest regeneration capacity (165).

4. INDICATORS AND THRESHOLDS OF DEGRADATION AND RECOVERY

The rapid global expansion of forest restoration initiatives has not been matched by clear strategies or criteria for evaluating success (166, 167). Identifying specific and unambiguous indicators of degradation and recovery is confounded by multiple interpretations of degradation and often by conflicting restoration objectives (168–170). Moreover, because a degraded forest remains standing, attributes of degradation are more subtle than demonstrating forest clearance. Levels of harvesting that lead to a loss of resilience and decline in production capacity can potentially be predicted from inventory data and stand production rates (155). Yet, our ability to detect and predict critical thresholds between alternate states in real ecosystems and landscapes lags well behind our ability to monitor and model them (162, 165). Remote sensing offers much potential, but its application to forest degradation and recovery remains challenging as structural changes often occur at scales below the detection capabilities of most remote sensing technologies (171). This is beginning to change, at least for relatively small-scale spatial assessments, and with the advent of low-cost unmanned aerial vehicles (121). At larger scales the UN Food and Agriculture Organization has developed a forest disturbance metric based on moderate resolution imaging spectroradiometer (MODIS) imagery of partial canopy cover reduction to detect disturbances due to fire, insect outbreaks, diseases, and severe weather events (172).

An added complexity is that degradation and recovery pathways and outcomes, represented by indicators such as biomass and species composition, are highly variable even among neighboring locations (80, 149, 173). Metrics also differ in their response pathways, which are shaped by past land uses and forest types (69). Biomass generally recovers quickly, but species diversity recovers more slowly, particularly in tropical as compared to temperate forests (69). Biogeochemical functions appear to recover more slowly on past agricultural lands than areas used for mining (69). Evaluating recovery debt or the success of restoration is therefore sensitive to the indicators chosen and to local, landscape, and regional contexts. This challenges our ability to identify the general principles of good restoration practice given that local site factors and stochasticity appear to have a major role in shaping the emergence of restoration outcomes. Restoration initiatives need to be accompanied by clear evaluation criteria and methods with the documented data available for synthesis if the science of restoration is to catch up with and inform restoration practice (167).

4.1. Indicators and Thresholds of Ecosystem Degradation and Recovery

Most studies that assess or monitor forest degradation or recovery use an operational definition that indicates a change (loss or gain) in a set of readily apparent ecosystem-level biophysical attributes, such as canopy cover, biomass, species richness and evenness, soil nutrients, organic carbon, structural variables such as canopy height or basal area distributions, or ecosystem services (174–177). Adopted thresholds largely result from arbitrary decisions negotiated among relevant stakeholders. In Gabon, for example, forests with standing biomass below 75 metric tons of carbon/ha are classified as degraded forests where oil palm developments are permitted (178). Shifting new agricultural production to these degraded lands will, it is argued, avoid new deforestation, dramatically reduce CO_2 emissions, and protect wildlife. Thus, assessments of forest degradation are often used to support changes in land use for food, fuel, and fiber production rather than to prescribe appropriate and cost-effective restoration interventions. Thresholds of forest biomass for land-use decisions could be quite distinct from thresholds relevant for loss or recovery of forest resilience or biodiversity.

Static biophysical attributes have limited ability to evaluate whether trajectories of forest change are leading to alternative persistent states or returning the forest ecosystem to its original state. Ideally, indicators should be tracked over time. Such attributes are often assumed to be proxies of more complex ecosystem-scale changes in, for example, the functioning of ecosystem processes, interaction complexity, or resilience. Rarely, however, are such links explicitly established. It is often difficult to characterize consistent changes in particular traits with successional development, particularly given unpredictable and divergent transitional pathways (139, 149).

Indicators that also function as drivers of change are particularly useful as they embody process-driven interactions. Biomass, for example, is a particularly strong driver and indicator of ecosystem recovery, especially during its early stages, as the effects of rapid biomass accumulation contribute substantially to functional properties shaping ecosystem processes (179). Other useful indicators of degradation and recovery include changes in ecological processes and disturbance regimes that regulate the flow of energy, species, and materials and that underlie ecosystem dynamics. Proxies of dynamics include spatial and temporal turnover of species and habitats within ecosystems (28, 155). Measures of forest regeneration, such as seed dispersal, seedling and sapling establishment, growth, and species turnover, provide more responsive information than the longer-term dynamics of larger tree stems (180, 181). The abundance of resprouts, soil seed banks, or the diversity and abundance of saplings constitute biological legacies that embody processes of forest recovery. These metrics encapsulate a process-oriented approach that conveys information about dynamics and trajectories without necessitating repeated measurement. Other rapid methods for ecosystem function assessment are being developed (182) and could subsequently be adapted as metrics of degradation based on ecosystem functions underpinning forest recovery.

4.2. Indicators and Thresholds of Land and Landscape Degradation and Recovery

At larger spatial scales, indicators of degradation and recovery employ proxy measures of tree canopy cover or forest cover. Because land degradation is often defined as a longstanding deterioration in ecosystem productivity, measures of primary productivity based on vegetation reflectance from remote sensing data can provide useful proxies. The Normalized Difference Vegetation Index (NDVI) is a widely used indicator of land degradation, particularly in dryland regions with sparse vegetation (183). The Global Land Degradation Assessment identified land degradation based on changes in vegetation greenness (measured by NDVI) and rain-use efficiency from 1981–2006 (184). A multiscale approach for assessing land and landscape degradation is highly recommended as coarse-scale indicators help identify broad hot spot areas that require more detailed investigation using more qualitative approaches. In the savannahs of Botswana, South Africa, a shift toward increasing woody vegetation, initially used as an indicator of landscape degradation based on NDVI values, was supplemented by fine-scale analysis of land-cover changes in shrublands, woodlands, and grasslands in areas that revealed large NDVI changes (185).

Indicators of landscape degradation in fragmented forest landscapes include the extent, size, and distribution of remaining forest fragments; an increase in edge habitat; and loss of connectivity and ecological memory (164, 186). Species presence in forest patches is strongly affected by the distribution of remaining habitat (187). In the highly fragmented Brazilian Atlantic Rainforest, areas with less than 24–33% forest cover showed marked declines in biodiversity suggesting thresholds of change (188). Remote sensing data can locate areas where habitat connectivity and watershed functions show persistent declines as well as changes in the areal extent and spatial configuration of different ecosystem types. These indicators of landscape degradation can also be used to target landscapes with a high potential for natural regeneration and restoration success (65).

Forest fragmentation is both an indicator and a driver of forest degradation as pervasive edge effects in small fragments can cause elevated tree mortality, biomass decline, alteration of forest microclimate, and cascading negative effects on species and functional group compositions (189–193). A simulation study in Brazil's Atlantic Forest found that isolated forest fragments below 25 ha in size showed altered structure and composition leading to a trajectory toward an alternate stable state (194). Indeed, rates of recovery appear to be inversely correlated with the extent of landscape fragmentation (46). Fragmentation indices might therefore provide some indication of the time required to achieve recovery or the type and scale of interventions required to accelerate it. Such interventions might include restoring vegetation in buffer zones or increasing connectivity of small forest fragments, which can potentially bolster forest patch resilience (65).

5. CONCLUSIONS: FROM DEGRADATION TO RECOVERY

Degradation is not a precisely defined concept. In common usage, it serves as a boundary object through which different actors can engage on a topic that is interpreted differently but has sufficient commonality of meaning to be broadly understood. Yet a biophysical approach to degradation unveils multiple complexities that typify complex adaptive systems and that stymie precise definitions. Conceptual limitations of degradation are exposed during the operationalization of management responses for restoration and recovery. To overcome such difficulties, degradation is frequently interpreted by reference to one or a few proxies, but even then degradation remains a largely arbitrary state that is given meaning only within a particular set of objectives and values.

An alternative approach is to consider degradation as a state that lacks, or has lost, the attributes of a complex adaptive system (28, 155, 195). Essentially, this means a condition in which ecosystem dynamics are greatly reduced or modified. Interactions and feedbacks are broken, and the ecosystem is confined to a persistent state in which key functions and attributes have been lost. Natural successional processes are arrested, and human intervention is required to restore a trajectory of recovery. Such a definition identifies lands or ecosystems that require active management interventions to restore ecosystem dynamics and successional trajectories, but it does not specify what direction those trajectories should take. This approach acknowledges that ecosystems are dynamic systems with many semipersistent equilibrium states and multiple successional or transitional pathways.

Restoration initiatives can adopt a combination of passive and active approaches, depending on the capacity for natural regeneration in targeted regions (31, 76, 176, 180) and the costs and benefits of intervention. Such costs can be quantified as recovery debt that accounts for the extent of disturbance and the current and projected rates of recovery (**Figure 2**). Conditions for natural regeneration are likely to be enhanced in areas initially treated with active restoration interventions such as tree planting, although the benefits of such interventions might be short lived (196) or indeed might have persistent legacies that diverge from natural regeneration outcomes

(68). Recovery of forest through natural regeneration might be more cost-effective at landscape scales, particularly as natural recovery processes might enhance landscape heterogeneity.

Clear definitions do not necessarily lead to more sustainable or better land use, which depends on the process by which decisions are made and how policies are formulated, implemented, and adaptively managed. Ultimately, and in view of the environmental challenges that lie ahead, a more important objective is to identify lands that have the greatest potential to deliver multiple restoration benefits. This approach might entail interventions to rescue lands from arrested succession, but it also might include prioritizing investments to accelerate recovery on lands where processes of recovery are slowed but not entirely terminated (65, 148).

Ecosystem and landscape degradation can be eliminated through cessation of practices that lead to degradation and accompanied by practices to restore and recover degraded areas and lands. Both approaches are important: Even if all of the currently degraded areas could be restored, degraded lands and ecosystems will continue to accumulate if the drivers of degradation persist. The importance of halting future land degradation underscores the need to implement sustainable land-use and production systems wherever and whenever possible. Practices of conservation, sustainable management, and ecosystem and landscape restoration are complementary and need to be effectively aligned to bring a halt to degradation and to foster long-term restoration efforts toward global and national targets.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

LITERATURE CITED

1. Food Agric. Organ. UN (FAO). 2011. *Assessing Forest Degradation: Towards the Development of Globally Applicable Guidelines*. Rome: FAO
2. Asner GP, Rudel TK, Aide TM, Defries R, Emerson R. 2009. A contemporary assessment of change in humid tropical forests. *Conserv. Biol.* 23:1386–95
3. Int. Trop. Timber Organ. (ITTO). 2002. *ITTO Guidelines for the Restoration, Management and Rehabilitation of Degraded and Secondary Tropical Forests*. Yokohama, Jpn.: Int. Trop. Timber Organ.
4. Willis KJ, Birks HJB. 2006. What is natural? The need for a long-term perspective in biodiversity conservation. *Science* 314:1261–65
5. Gilliam FS. 2016. Forest ecosystems of temperate climatic regions: from ancient use to climate change. *New Phytol.* 212:871–87
6. Wroe S, Field J, Grayson DK. 2006. Megafaunal extinction: climate, humans and assumptions. *Trends Ecol. Evol.* 21:61–62
7. Diamond J. 2005. *Collapse: How Societies Choose to Fail or Succeed*. London, UK: Viking
8. Tainter JA. 2006. Archaeology of overshoot and collapse. *Annu. Rev. Anthropol.* 35:59–74
9. Jacks GV, Whyte RO. 1939. *The Rape of the Earth: A World Survey of Soil Erosion*. London: Faber & Faber
10. Osborn F. 1948. *Our Plundered Planet*. Boston, MA: Little, Brown
11. Leopold A. 1949. *A Sand County Almanac*. Oxford, UK: Oxford Univ. Press
12. Carson R. 1962. *Silent Spring*. New York: Houghton Mifflin
13. UN Conv. Combat Desertif. (UN CCD). 2011. *Submission by the United Nations Convention to Combat Desertification on Decision 6/CP.17*. Bonn, Ger: UN CCD. **http://unfccc.int/resource/docs/2012/smsn/igo/99.pdf**
14. Veldman JW. 2016. Clarifying the confusion: old-growth savannahs and tropical ecosystem degradation. *Philos. Trans. R. Soc. B* 371:20150306

15. Morales-Barquero L, Skutsch M, Jardel-Peláez EJ, Ghilardi A, Kleinn C, Healey JR. 2014. Operationalizing the definition of forest degradation for REDD+, with application to Mexico. *Forests* 5:1653–81
16. Blaikie P, Brookfield H. 1987. *Land Degradation and Society*. London: Methuen
17. Hobbs RJ. 2016. Degraded or just different? Perceptions and value judgements in restoration decisions. *Restor. Ecol.* 24:153–58
18. Sasaki N, Putz FE. 2009. Critical need for new definitions of "forest" and "forest degradation" in global climate change agreements. *Conserv. Lett.* 2:226–32
19. Schmidt-Vogt D. 1998. Defining degradation: the impacts of swidden on forests in northern Thailand. *Mt. Res. Dev.* 18:135–49
20. McElwee P. 2009. Reforesting "bare hills" in Vietnam: social and environmental consequences of the 5 million hectare reforestation program. *Ambio* 38:325–33
21. Chazdon RL, Brancalion PHS, Laestadius L, Bennett-Curry A, Buckingham K, et al. 2016. When is a forest a forest? Forest concepts and definitions in the era of forest and landscape restoration. *Ambio* 45:538–50
22. Filer C, Keenan RJ, Allen BJ, McAlpine JR. 2009. Deforestation and forest degradation in Papua New Guinea. *Ann. Forest Sci.* 66:813
23. Filotas E, Parrott L, Burton PJ, Chazdon RL, Coates KD, et al. 2014. Viewing forests through the lens of complex systems science. *Ecosphere* 5:1–23
24. Messier C, Puettmann K, Chazdon R, Andersson KP, Angers VA, et al. 2015. From management to stewardship: viewing forests as complex adaptive systems in an uncertain world. *Conserv. Lett.* 8:368–77
25. Moreno-Mateos D, Barbier EB, Jones PC, Jones HP, Aronson J, et al. 2017. Anthropogenic ecosystem disturbance and the recovery debt. *Nat. Commun.* 8:14163
26. Lamb D, Stanturf J, Madsen P. 2012. What is forest landscape restoration? In *Forest Landscape Restoration: Integrating Natural and Social Sciences*, ed. J Stanturf, D Lamb, P Madsen, pp. 3–23. Dordrecht, Neth.: Springer Sci.
27. Burger J, Gochfeld M, Pletnikoff K, Snigaroff R, Snigaroff D, Stamm T. 2008. Ecocultural attributes: evaluating ecological degradation in terms of ecological goods and services versus subsistence and tribal values. *Risk Anal.* 28:1261–72
28. Ghazoul J, Burivalova Z, Garcia-Ulloa J, King L. 2015. Conceptualizing forest degradation. *Trends Ecol. Evol.* 30:622–32
29. Kardol P, Wardle DA. 2010. How understanding aboveground-belowground linkages can assist restoration ecology. *Trends Ecol. Evol.* 25:670–79
30. Gourlet-Fleury S, Rossi V, Rejou-Mechain M, Freycon V, Fayolle A, et al. 2011. Environmental filtering of dense-wooded species controls above-ground biomass stored in African moist forests. *J. Ecol.* 99:981–90
31. Chazdon RL. 2003. Tropical forest recovery: legacies of human impact and natural disturbances. *Perspect. Plant Ecol. Evol. Syst.* 6:51–71
32. Islam KR, Ahmed MR, Bhuiyan MK, Badruddin A. 2001. Deforestation effects on vegetative regeneration and soil quality in tropical semi-evergreen degraded and protected forests of Bangladesh. *Land Degrad. Dev.* 12:45–56
33. Labriere N, Laumonier Y, Locatelli B, Vieilledent G, Comptour M. 2015. Ecosystem services and biodiversity in a rapidly transforming landscape in northern Borneo. *PLOS ONE* 10:e0140423
34. Sidle RC, Ziegler AD, Negishi JN, Nik AR, Siew R, Turkelboom F. 2006. Erosion processes in steep terrain: truths, myths, and uncertainties related to forest management in Southeast Asia. *For. Ecol. Manag.* 224:199–225
35. Sloan S. 2008. Reforestation amidst deforestation: simultaneity and succession. *Glob. Environ. Change Hum. Policy Dimens.* 18:425–41
36. Thompson J, Brokaw N, Zimmerman JK, Waide RB, Everham EM, et al. 2002. Land use history, environment, and tree composition in a tropical forest. *Ecol. Appl.* 12:1344–63
37. Johst K, Drechsler M, van Teeffelen AJA, Hartig F, Vos CC, et al. 2011. Biodiversity conservation in dynamic landscapes: trade-offs between number, connectivity and turnover of habitat patches. *J. Appl. Ecol.* 48:1227–35

38. Mitchell MGF, Bennett EM, Gonzalez A. 2015. Strong and nonlinear effects of fragmentation on ecosystem service provision at multiple scales. *Environ. Res. Lett.* 10:094014
39. Ruzicka KJ, Groninger JW, Zaczek JJ. 2010. Deer browsing, forest edge effects, and vegetation dynamics following bottomland forest restoration. *Restor. Ecol.* 18:702–10
40. Tanentzap AJ, Burrows LE, Lee WG, Nugent G, Maxwell JM, Coomes DA. 2009. Landscape-level vegetation recovery from herbivory: progress after four decades of invasive red deer control. *J. Appl. Ecol.* 46:1064–72
41. Doyle M, Drew CA, eds. 2008. *Large-Scale Ecosystem Restoration: Five Case Studies from the United States*. Washington, DC: Island
42. Sabogal C, Besacier C, McGuire D. 2015. Forest and landscape restoration: concepts, approaches and challenges for implementation. *Unasylva* 66:3–10
43. Rudel TK. 2005. *Tropical Forests: Regional Pathways of Destruction and Regeneration in the Late Twentieth Century*. New York: Columbia Univ. Press
44. Lambin EF. 1999. Monitoring forest degradation in tropical regions by remote sensing: some methodological issues. *Glob. Ecol. Biogeogr.* 8:191–98
45. Thompson ID, Guariguata MR, Okabe K, Bahamondez C, Nasi R, et al. 2013. An operational framework for defining and monitoring forest degradation. *Ecol. Soc.* 18:20
46. Crouzeilles R, Curran M, Ferreira MS, Lindenmayer DB, Grelle CEV, Benayas JMR. 2016. A global meta-analysis on the ecological drivers of forest restoration success. *Nat. Commun.* 7:11666
47. Robbins P, Fraser A. 2003. A forest of contradictions: producing the landscapes of the Scottish highlands. *Antipode* 35:95–118
48. Stott PA, Sullivan S, eds. 2000. *Political Ecology: Science, Myth and Power*. London: Arnold
49. Cairns MF. 2015. *Shifting Cultivation and Environmental Change: Indigenous People, Agriculture and Forest Conservation*. Abingdon, UK: Routledge
50. van Vliet N, Mertz O, Heinimann A, Langanke T, Pascual U, et al. 2012. Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: a global assessment. *Glob. Environ. Change Hum. Policy Dimens.* 22:418–29
51. Mertz O, Padoch C, Fox J, Cramb RA, Leisz SJ, et al. 2009. Swidden change in Southeast Asia: understanding causes and consequences. *Hum. Ecol.* 37:259–64
52. de Carvalho CM, Silveira S, La Rovere EL, Iwama AY. 2015. Deforested and degraded land available for the expansion of palm oil for biodiesel in the state of Pará in the Brazilian Amazon. *Renew. Sustain. Energy Rev.* 44:867–76
53. Edwards DP, Tobias JA, Sheil D, Meijaard E, Laurance WF. 2014. Maintaining ecosystem function and services in logged tropical forests. *Trends Ecol. Evol.* 29:511–20
54. Thomas HJD, Paterson JS, Metzger MJ, Sing L. 2015. Towards a research agenda for woodland expansion in Scotland. *For. Ecol. Manag.* 349:149–61
55. Patru-Stupariu I, Tudor CA, Stupariu MS, Buttler A, Peringer A. 2016. Landscape persistence and stakeholder perspectives: the case of Romania's Carpathians. *Appl. Geogr.* 69:87–98
56. Price B, Kienast F, Seidl I, Ginzler C, Verburg PH, Bolliger J. 2015. Future landscapes of Switzerland: risk areas for urbanisation and land abandonment. *Appl. Geogr.* 57:32–41
57. Ray R, Chandran MDS, Ramachandra TV. 2014. Socio-cultural protection of endemic trees in humanised landscape. *Biodivers. Conserv.* 23:1977–94
58. Sowinska-Swierkosz B, Chmielewski TJ. 2014. Comparative assessment of public opinion on the landscape quality of two biosphere reserves in Europe. *Environ. Manag.* 54:531–56
59. Star SL. 2010. This is not a boundary object: reflections on the origin of a concept. *Sci. Technol. Hum. Values* 35:601–17
60. Cash DW, Clark WC, Alcock F, Dickson NM, Eckley N, et al. 2003. Knowledge systems for sustainable development. *PNAS* 100:8086–91
61. Abson DJ, von Wehrden H, Baumgartner S, Fischer J, Hanspach J, et al. 2014. Ecosystem services as a boundary object for sustainability. *Ecol. Econ.* 103:29–37
62. Chazdon RL, Laestadius L. 2016. Forest and landscape restoration: toward a shared vision and vocabulary. *Am. J. Bot.* 103:1869–71

63. McCormick N, Jenkins M, Maginnis S. 2014. *Biofuels and Degraded Land: The Potential Role of Intensive Agriculture in Landscape Restoration*. Gland, Switz.: IUCN

64. Stefanes M, Ochoa-Quintero JM, de Oliveira Roque F, Sugai LSM, Tambosi LR, et al. 2016. Incorporating resilience and cost in ecological restoration strategies at landscape scale. *Ecol. Soc.* 21:54

65. Tambosi LR, Martensen AC, Ribeiro MC, Metzger JP. 2014. A framework to optimize biodiversity restoration efforts based on habitat amount and landscape connectivity. *Restor. Ecol.* 22:169–77

66. Alves-Pinto HN, Latawiec AE, Strassburg BBN, Barros FSM, Sansevero JBB, et al. 2017. Reconciling rural development and ecological restoration: strategies and policy recommendations for the Brazilian Atlantic Forest. *Land Use Policy* 60:419–26

67. Latawiec AE, Strassburg BBN, Brancalion PHS, Rodrigues RR, Gardner T. 2015. Creating space for large-scale restoration in tropical agricultural landscapes. *Front. Ecol. Environ.* 13:211–18

68. Murcia C. 1997. Evaluation of Andean alder as a catalyst for the recovery of tropical cloud forests in Colombia. *For. Ecol. Manag.* 99:163–70

69. Meli P, Holl KD, Benayas JMR, Jones HP, Jones PC, et al. 2017. A global review of past land use, climate, and active versus passive restoration effects on forest recovery. *PLOS ONE* 12:e0171368

70. de Souza HN, de Graaff J, Pulleman MM. 2012. Strategies and economics of farming systems with coffee in the Atlantic Rainforest Biome. *Agrofor. Syst.* 84:227–42

71. Le HD, Smith C, Herbohn J. 2014. What drives the success of reforestation projects in tropical developing countries? The case of the Philippines. *Glob. Environ. Change Hum. Policy Dimens.* 24:334–48

72. Richards RC, Rerolle J, Aronson J, Pereira PH, Goncalyes H, Brancalion PHS. 2015. Governing a pioneer program on payment for watershed services: stakeholder involvement, legal frameworks and early lessons from the Atlantic forest of Brazil. *Ecosyst. Serv.* 16:23–32

73. Suding KN, Hobbs RJ. 2009. Threshold models in restoration and conservation: a developing framework. *Trends Ecol. Evol.* 24:271–79

74. Birch JC, Newton AC, Aquino CA, Cantarello E, Echeverria C, et al. 2010. Cost-effectiveness of dryland forest restoration evaluated by spatial analysis of ecosystem services. *PNAS* 107:21925–30

75. Vergara W, Lomeli LG, Rios AR, Isbell P, Prager S, De Camino R. 2016. *The Economic Case for Landscape Restoration in Latin America*. Washington, DC: World Resour. Inst.

76. Brancalion PHS, Schweizer D, Gaudare U, Mangueira JR, Lamonato F, et al. 2016. Balancing economic costs and ecological outcomes of passive and active restoration in agricultural landscapes: the case of Brazil. *Biotropica* 48:856–67

77. Franklin JF, Hagmann RK, Urgenson LS. 2014. Interactions between societal goals and restoration of dry forest landscapes in western North America. *Landsc. Ecol.* 29:1645–55

78. Moritz MA, Batllori E, Bradstock RA, Gill AM, Handmer J, et al. 2014. Learning to coexist with wildfire. *Nature* 515:58–66

79. Ryan KC, Knapp EE, Varner JM. 2013. Prescribed fire in North American forests and woodlands: history, current practice, and challenges. *Front. Ecol. Environ.* 11:E15–24

80. Mesquita RDG, Massoca PED, Jakovac CC, Bentos TV, Williamson GB. 2015. Amazon rain forest succession: stochasticity or land-use legacy? *BioScience* 65:849–61

81. Li SY, Verburg PH, Lv SH, Wu JL, Li XB. 2012. Spatial analysis of the driving factors of grassland degradation under conditions of climate change and intensive use in Inner Mongolia, China. *Reg. Environ. Change* 12:461–74

82. Hanson C, Buckingham K, DeWitt S, Laestadius L. 2015. *The Restoration Diagnostic. A Method for Developing Forest Landscape Restoration Strategies by Rapidly Assessing the Status of Key Success Factors*. Washington, DC: World Resour. Inst.

83. Hiers JK, Jackson ST, Hobbs RJ, Bernhardt ES, Valentine LE. 2016. The precision problem in conservation and restoration. *Trends Ecol. Evol.* 31:820–30

84. Hughes FMR, Adams WM, Stroh PA. 2012. When is open-endedness desirable in restoration projects? *Restor. Ecol.* 20:291–95

85. Chapin FS, Carpenter SR, Kofinas GP, Folke C, Abel N, et al. 2010. Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trends Ecol. Evol.* 25:241–49

86. Petraitis P. 2013. *Multiple Stable States in Natural Ecosystems*. Oxford, UK: Oxford Univ. Press

87. Hirota M, Holmgren M, Van Nes EH, Scheffer M. 2011. Global resilience of tropical forest and savanna to critical transitions. *Science* 334:232–35
88. Martinez-Garza C, Osorio-Beristain M, Valenzuela-Galvan D, Nicolás-Medina A. 2011. Intra and inter-annual variation in seed rain in a secondary dry tropical forest excluded from chronic disturbance. *For. Ecol. Manag.* 262:2207–18
89. Souza JT, Ferraz EMN, Albuquerque UP, Araújo EL. 2014. Does proximity to a mature forest contribute to the seed rain and recovery of an abandoned agriculture area in a semiarid climate? *Plant Biol.* 16:748–56
90. Standish RJ, Hobbs RJ, Mayfield MM, Bestelmeyer BT, Suding KN, et al. 2014. Resilience in ecology: abstraction, distraction, or where the action is? *Biol. Conserv.* 177:43–51
91. Bowman DMJS, Balch J, Artaxo P, Bond WJ, Cochrane MA, et al. 2011. The human dimension of fire regimes on Earth. *J. Biogeogr.* 38:2223–36
92. Cochrane MA, Alencar A, Schulze MD, Souza CM Jr., Lefebvre P, Nepstad DC. 2002. Investigating positive feedbacks in the fire dynamic of closed canopy tropical forests. In *Deforestation and Land Use in the Amazon*, ed. CH Wood, R Porro, pp. 285–98. Gainesville, FL: Univ. Press Florida
93. Mori AS, Furukawa T, Sasaki T. 2013. Response diversity determines the resilience of ecosystems to environmental change. *Biol. Rev.* 88:349–64
94. Aslan CE, Bronstein JL, Rogers HS, Gedan KB, Brodie J, et al. 2016. Leveraging nature's backup plans to incorporate interspecific interactions and resilience into restoration. *Restor. Ecol.* 24:434–40
95. Churchill DJ, Larson AJ, Dahlgreen MC, Franklin JF, Hessburg PF, Lutz JA. 2013. Restoring forest resilience: from reference spatial patterns to silvicultural prescriptions and monitoring. *For. Ecol. Manag.* 291:442–57
96. Strahan RT, Meador AJS, Huffman DW, Laughlin DC. 2016. Shifts in community-level traits and functional diversity in a mixed conifer forest: a legacy of land-use change. *J. Appl. Ecol.* 53:1755–65
97. Laliberte E, Wells JA, DeClerck F, Metcalfe DJ, Catterall CP, et al. 2010. Land-use intensification reduces functional redundancy and response diversity in plant communities. *Ecol. Lett.* 13:76–86
98. Cavallero L, Lopez DR, Raffaele E, Aizen MA. 2015. Structural-functional approach to identify post-disturbance recovery indicators in forests from northwestern Patagonia: a tool to prevent state transitions. *Ecol. Indic.* 52:85–95
99. van der Putten WH, Bardgett RD, Bever JD, Bezemer TM, Casper BB, et al. 2013. Plant-soil feedbacks: the past, the present and future challenges. *J. Ecol.* 101:265–76
100. Ripple WJ, Beschta RL, Painter LE. 2015. Trophic cascades from wolves to alders in Yellowstone. *For. Ecol. Manag.* 354:254–60
101. Wallach AD, Ripple WJ, Carroll SP. 2015. Novel trophic cascades: apex predators enable coexistence. *Trends Ecol. Evol.* 30:146–53
102. Blackham GV, Webb EL, Corlett RT. 2014. Natural regeneration in a degraded tropical peatland, central Kalimantan, Indonesia: implications for forest restoration. *For. Ecol. Manag.* 324:8–15
103. Kaiser-Bunbury CN, Mougal J, Whittington AE, Valentin T, Gabriel R, et al. 2017. Ecosystem restoration strengthens pollination network resilience and function. *Nature* 542:223–27
104. Kollmann J, Meyer ST, Bateman R, Conradi T, Gossner MM, et al. 2016. Integrating ecosystem functions into restoration ecology: recent advances and future directions. *Restor. Ecol.* 24:722–30
105. Doherty JM, Callaway JC, Zedler JB. 2011. Diversity-function relationships changed in a long-term restoration experiment. *Ecol. Appl.* 21:2143–55
106. Morelli F, Tryjanowski P. 2016. The dark side of the "redundancy hypothesis" and ecosystem assessment. *Ecol. Complexity* 28:222–29
107. Bustamante-Sanchez MA, Armesto JJ. 2012. Seed limitation during early forest succession in a rural landscape on Chiloe Island, Chile: implications for temperate forest restoration. *J. Appl. Ecol.* 49:1103–12
108. Leite MD, Tambosi LR, Romitelli I, Metzger JP. 2013. Landscape ecology perspective in restoration projects for biodiversity conservation: a review. *Nat. Conserv.* 11:108–18
109. Craven D, Filotas E, Angers VA, Messier C. 2016. Evaluating resilience of tree communities in fragmented landscapes: linking functional response diversity with landscape connectivity. *Divers. Distrib.* 22:505–18

110. van der Plas F, Manning P, Soliveres S, Allan E, Scherer-Lorenzen M, et al. 2016. Biotic homogenization can decrease landscape-scale forest multifunctionality. *PNAS* 113:3557–62
111. Schulte LA, Mladenoff DJ, Crow TR, Merrick LC, Cleland DT. 2007. Homogenization of northern US Great Lakes forests due to land use. *Landsc. Ecol.* 22:1089–103
112. Thompson JR, Carpenter DN, Cogbill CV, Foster DR. 2013. Four centuries of change in northeastern United States forests. *PLOS ONE* 8:e72540
113. Kelly LT, Brotons L. 2017. Using fire to promote biodiversity. *Science* 355:1264–65
114. Charnley S, Spies TA, Barros AM, White EM, Olsen KA. 2017. Diversity in forest management to reduce wildfire losses: implications for resilience. *Ecol. Soc.* 22:22
115. Hessburg PF, Churchill DJ, Larson AJ, Haugo RD, Miller C, et al. 2015. Restoring fire-prone inland Pacific landscapes: seven core principles. *Landsc. Ecol.* 30:1805–35
116. Tingley MW, Ruiz-Gutierrez V, Wilkerson RL, Howell CA, Siegel RB. 2016. Pyrodiversity promotes avian diversity over the decade following forest fire. *Proc. R. Soc. B* 283:20161703
117. Turner MG. 2010. Disturbance and landscape dynamics in a changing world. *Ecology* 91:2833–49
118. Frelich LE, Reich PB. 1999. Neighborhood effects, disturbance severity, and community stability in forests. *Ecosystems* 2:151–66
119. Prasad AE. 2012. Landscape-scale relationships between the exotic invasive shrub *Lantana camara* and native plants in a tropical deciduous forest in southern India. *J. Trop. Ecol.* 28:55–64
120. McCune JL, Vellend M. 2013. Gains in native species promote biotic homogenization over four decades in a human-dominated landscape. *J. Ecol.* 101:1542–51
121. Zahawi RA, Dandois JP, Holl KD, Nadwodny D, Reid JL, Ellis EC. 2015. Using lightweight unmanned aerial vehicles to monitor tropical forest recovery. *Biol. Conserv.* 186:287–95
122. Cho MA, Ramoelo A, Debba P, Mutanga O, Mathieu R, et al. 2013. Assessing the effects of subtropical forest fragmentation on leaf nitrogen distribution using remote sensing data. *Landsc. Ecol.* 28:1479–91
123. Malhi Y, Gardner TA, Goldsmith GR, Silman MR, Zelazowski P. 2014. Tropical forests in the Anthropocene. *Annu. Rev. Environ. Resourc.* 39:125–59
124. Jackson ST, Hobbs RJ. 2009. Ecological restoration in the light of ecological history. *Science* 325:567–69
125. Balaguer L, Escudero A, Martin-Duque JF, Mola I, Aronson J. 2014. The historical reference in restoration ecology: re-defining a cornerstone concept. *Biol. Conserv.* 176:12–20
126. Hobbs RJ, Higgs E, Harris JA. 2009. Novel ecosystems: implications for conservation and restoration. *Trends Ecol. Evol.* 24:599–605
127. Josefsson T, Hornberg G, Ostlund L. 2009. Long-term human impact and vegetation changes in a boreal forest reserve: implications for the use of protected areas as ecological references. *Ecosystems* 12:1017–36
128. van Gemerden BS, Olff H, Parren MPE, Bongers F. 2003. The pristine rain forest? Remnants of historical human impacts on current tree species composition and diversity. *J. Biogeogr.* 30:1381–90
129. Gomez-Pompa A, Kaus A. 1992. Taming the wilderness myth. *BioScience* 42:271–79
130. Heckenberger MJ, Russell JC, Toney JR, Schmidt MJ. 2007. The legacy of cultural landscapes in the Brazilian Amazon: implications for biodiversity. *Philos. Trans. R. Soc. B* 362:197–208
131. Gourlet-Fleury S, Beina D, Fayolle A, Ouedraogo DY, Mortier F, et al. 2013. Silvicultural disturbance has little impact on tree species diversity in a central African moist forest. *For. Ecol. Manag.* 304:322–32
132. Truitt AM, Granek EF, Duveneck MJ, Goldsmith KA, Jordan MP, Yazzie KC. 2015. What is novel about novel ecosystems: managing change in an ever-changing world. *Environ. Manag.* 55:1217–26
133. Mascaro J, Hughes RF, Schnitzer SA. 2012. Novel forests maintain ecosystem processes after the decline of native tree species. *Ecol. Monogr.* 82:221–38
134. Kitchen SG. 2012. Historical fire regime and forest variability on two eastern Great Basin fire-sheds (USA). *For. Ecol. Manag.* 285:53–66
135. Addington RN, Knapp BO, Sorrell GG, Elmore ML, Wang GG, Walker JL. 2015. Factors affecting broadleaf woody vegetation in upland pine forests managed for longleaf pine restoration. *For. Ecol. Manag.* 354:130–38
136. Pasanen H, Rehu V, Junninen K, Kouki J. 2015. Prescribed burning of canopy gaps facilitates tree seedling establishment in restoration of pine-dominated boreal forests. *Can. J. For. Res.* 45:1225–31
137. Taylor RS, Watson SJ, Nimmo DG, Kelly LT, Bennett AF, Clarke MF. 2012. Landscape-scale effects of fire on bird assemblages: Does pyrodiversity beget biodiversity? *Divers. Distrib.* 18:519–29

138. Olander LP, Gibbs HK, Steininger M, Swenson JJ, Murray BC. 2008. Reference scenarios for deforestation and forest degradation in support of REDD: a review of data and methods. *Environ. Res. Lett.* 3:025011
139. Frelich LE, Reich PB. 1995. Spatial patterns and succession in a Minnesota southern-boreal forest. *Ecol. Monogr.* 65:325–46
140. Walker B, Holling CS, Carpenter SR, Kinzig A. 2004. Resilience, adaptability and transformability in social-ecological systems. *Ecol. Soc.* 9:5
141. Newton AC, Cantarello E. 2015. Restoration of forest resilience: an achievable goal? *New For*. 46:645–68
142. Haeussler S, Canham C, Coates KD. 2013. Complexity in temperate forest dynamics. In *Managing Forests as Complex Adaptive Systems: Building Resilience to the Challenge of Global Change*, ed. C Messier, KJ Puettmann, KD Coates, pp. 60–78. Abingdon, UK: Routledge
143. Peterken GF, Jones EW. 1987. Forty years of change in Lady Park Wood: the old-growth stands. *J. Ecol.* 75:477–512
144. Longworth JB, Mesquita RC, Bentos TV, Moreira MP, Massoca PE, Williamson GB. 2014. Shifts in dominance and species assemblages over two decades in alternative successions in central Amazonia. *Biotropica* 46:529–37
145. Williamson GB, Bentos TV, Longworth JB, Mesquita RCG. 2014. Convergence and divergence in alternative successional pathways in central Amazonia. *Plant Ecol. Divers.* 7:341–48
146. Krause A, Pugh TAM, Bayer AD, Lindeskog M, Arneth A. 2016. Impacts of land-use history on the recovery of ecosystems after agricultural abandonment. *Earth Syst. Dyn.* 7:745–66
147. Jakovac CC, Pena-Claros M, Kuyper TW, Bongers F. 2015. Loss of secondary-forest resilience by land-use intensification in the Amazon. *J. Ecol.* 103:67–77
148. Arroyo-Rodriguez V, Melo FPL, Martinez-Ramos M, Bongers F, Chazdon RL, et al. 2017. Multiple successional pathways in human-modified tropical landscapes: new insights from forest succession, forest fragmentation and landscape ecology research. *Biol. Rev.* 92:326–40
149. Norden N, Angarita HA, Bongers F, Martinez-Ramos M, Granzow-de la Cerda I, et al. 2015. Successional dynamics in Neotropical forests are as uncertain as they are predictable. *PNAS* 112:8013–18
150. Bengtsson J, Angelstam P, Elmqvist T, Emanuelsson U, Folke C, et al. 2003. Reserves, resilience and dynamic landscapes. *Ambio* 32:389–96
151. Jakovac ACC, Bentos TV, Mesquita RCG, Williamson GB. 2014. Age and light effects on seedling growth in two alternative secondary successions in central Amazonia. *Plant Ecol. Divers.* 7:349–58
152. Schnitzer SA, Carson WP. 2010. Lianas suppress tree regeneration and diversity in treefall gaps. *Ecol. Lett.* 13:849–57
153. Wagner A, Yap DLT, Yap HT. 2015. Drivers and consequences of land use patterns in a developing country rural community. *Agric. Ecosyst. Environ.* 214:78–85
154. Anderson RC, Schwegman JE, Anderson MR. 2000. Micro-scale restoration: a 25-year history of a southern Illinois barrens. *Restor. Ecol.* 8:296–306
155. Bahamondez C, Thompson ID. 2016. Determining forest degradation, ecosystem state and resilience using a standard stand stocking measurement diagram: theory into practice. *Forestry* 89:290–300
156. Lugo AE, Scatena FN, Silver WL, Molina Colon S, Murphy PG. 2002. Resilience of tropical wet and dry forests in Puerto Rico. In *Resilience and the Behavior of Large-Scale Systems*, ed. LH Gunderson, L Pritchard, pp. 195–226. Washington, DC: Island
157. Chazdon RL, Arroyo JP. 2013. Tropical forests as complex adaptive systems. See Ref. 142, pp. 35–59
158. Lawrence D, Radel C, Tully K, Schmook B, Schneider L. 2010. Untangling a decline in tropical forest resilience: constraints on the sustainability of shifting cultivation across the globe. *Biotropica* 42:21–30
159. Beaune D, Bretagnolle F, Bollache L, Hohmann G, Surbeck M, Fruth B. 2013. Seed dispersal strategies and the threat of defaunation in a Congo forest. *Biodivers. Conserv.* 22:225–38
160. Peres CA, Emilio T, Schietti J, Desmouliere SJM, Levi T. 2016. Dispersal limitation induces long-term biomass collapse in overhunted Amazonian forests. *PNAS* 113:892–97
161. Anderson-Teixeira KJ, Miller AD, Mohan JE, Hudiburg TW, Duval BD, DeLucia EH. 2013. Altered dynamics of forest recovery under a changing climate. *Glob. Change Biol.* 19:2001–21
162. Reyer CPO, Brouwers N, Rammig A, Brook BW, Epila J, et al. 2015. Forest resilience and tipping points at different spatio-temporal scales: approaches and challenges. *J. Ecol.* 103:5–15

163. Rozendaal DMA, Chazdon RL, Arreola-Villa F, Balvanera P, Bentos TV, et al. 2016. Demographic drivers of aboveground biomass dynamics during secondary succession in Neotropical dry and wet forests. *Ecosystems* 20:340–53
164. Pardini R, Bueno AD, Gardner TA, Prado PI, Metzger JP. 2010. Beyond the fragmentation threshold hypothesis: regime shifts in biodiversity across fragmented landscapes. *PLOS ONE* 5:e13666
165. Magnuszewski P, Ostasiewicz K, Chazdon R, Salk C, Pajak M, et al. 2015. Resilience and alternative stable states of tropical forest landscapes under shifting cultivation regimes. *PLOS ONE* 10:e0137497
166. Wortley L, Hero JM, Howes M. 2013. Evaluating ecological restoration success: a review of the literature. *Restor. Ecol.* 21:537–43
167. Shoo LP, Catterall CP. 2013. Stimulating natural regeneration of tropical forest on degraded land: approaches, outcomes, and information gaps. *Restor. Ecol.* 21:670–77
168. Bateman HL, Merritt DM, Johnson JB. 2012. Riparian forest restoration: conflicting goals, trade-offs, and measures of success. *Sustainability* 4:2334–47
169. Buergin R. 2016. Ecosystem restoration concessions in Indonesia: conflicts and discourses. *Crit. Asian Stud.* 48:278–301
170. Ager AA, Day MA, Vogler K. 2016. Production possibility frontiers and socioecological tradeoffs for restoration of fire adapted forests. *J. Environ. Manag.* 176:157–68
171. Shimizu K, Ponce-Hernandez R, Ahmed OS, Ota T, Win ZC, et al. 2016. Using Landsat time series imagery to detect forest disturbance in selectively logged tropical forests in Myanmar. *Can. J. For. Res.* 47:289–96
172. van Lierop P, Lindquist E, Sathyapala S, Franceschini G. 2015. Global forest area disturbance from fire, insect pests, diseases and severe weather events. *For. Ecol. Manag.* 352:78–88
173. Holl KD, Zahawi RA. 2014. Factors explaining variability in woody above-ground biomass accumulation in restored tropical forest. *For. Ecol. Manag.* 319:36–43
174. Bustamante MMC, Roitman I, Aide TM, Alencar A, Anderson LO, et al. 2016. Toward an integrated monitoring framework to assess the effects of tropical forest degradation and recovery on carbon stocks and biodiversity. *Glob. Change Biol.* 22:92–109
175. Chidumayo EN. 2013. Forest degradation and recovery in a Miombo woodland landscape in Zambia: 22 years of observations on permanent sample plots. *For. Ecol. Manag.* 291:154–61
176. Shoo LP, Freebody K, Kanowski J, Catterall CP. 2016. Slow recovery of tropical old-field rainforest regrowth and the value and limitations of active restoration. *Conserv. Biol.* 30:121–32
177. Xu H, Li YD, Liu SR, Zang RG, He FL, Spence JR. 2015. Partial recovery of a tropical rain forest a half-century after clear-cut and selective logging. *J. Appl. Ecol.* 52:1044–52
178. Austin KG, Lee ME, Clark C, Forester BR, Urban DL, et al. 2017. An assessment of high carbon stock and high conservation value approaches to sustainable oil palm cultivation in Gabon. *Environ. Res. Lett.* 12:014005
179. Lohbeck M, Poorter L, Martinez-Ramos M, Bongers F. 2015. Biomass is the main driver of changes in ecosystem process rates during tropical forest succession. *Ecology* 96:1242–52
180. Norden N, Chazdon RL, Chao A, Jiang Y-H, Vilchez-Alvarado B. 2009. Resilience of tropical rain forests: tree community reassembly in secondary forests. *Ecol. Lett.* 12:385–94
181. Buma B, Wessman CA. 2011. Disturbance interactions can impact resilience mechanisms of forests. *Ecosphere* 2:1–13
182. Meyer ST, Koch C, Weisser WW. 2015. Towards a standardized Rapid Ecosystem Function Assessment (REFA). *Trends Ecol. Evol.* 30:390–97
183. Rishmawi K, Prince SD. 2016. Environmental and anthropogenic degradation of vegetation in the Sahel from 1982 to 2006. *Remote Sens.* 8:948
184. Yengoh GT, Dent D, Olsson L, Tengberg AE, Tucker III CJ. 2015. Key issues in the use of NDVI for land degradation assessment. In *Use of the Normalized Difference Vegetation Index (NDVI) to Assess Land Degradation at Multiple Scales: Current Status, Future Trends, and Practical Considerations*, ed. GT Yengoh, D Dent, L Olsson L, AE Tengberg, CJ Tucker III, pp. 31–35. Cham, Switz.: Springer Int.
185. Herrero HV, Southworth J, Bunting E. 2016. Utilizing multiple lines of evidence to determine landscape degradation within protected area landscapes: a case study of Chobe National Park, Botswana from 1982 to 2011. *Remote Sens.* 8:623

186. Zahawi RA, Duran G, Kormann U. 2015. Sixty-seven years of land-use change in southern Costa Rica. *PLOS ONE* 10:e0143554
187. Banks-Leite C, Ewers RM, Metzger JP. 2012. Unraveling the drivers of community dissimilarity and species extinction in fragmented landscapes. *Ecology* 93:2560–69
188. Banks-Leite C, Pardini R, Tambosi LR, Pearse WD, Bueno AA, et al. 2014. Using ecological thresholds to evaluate the costs and benefits of set-asides in a biodiversity hotspot. *Science* 345:1041–45
189. Pütz S, Groeneveld J, Henle K, Knogge C, Martensen AC, et al. 2014. Long-term carbon loss in fragmented Neotropical forests. *Nat. Commun.* 5:5037
190. Brinck K, Fischer R, Groeneveld J, Lehmann S, De Paula MD, et al. 2017. High resolution analysis of tropical forest fragmentation and its impact on the global carbon cycle. *Nat. Commun.* 8:14855
191. Lobo D, Leao T, Melo FPL, Santos AMM, Tabarelli M. 2011. Forest fragmentation drives Atlantic forest of northeastern Brazil to biotic homogenization. *Divers. Distrib.* 17:287–96
192. Lopes AV, Girao LC, Santos BA, Peres CA, Tabarelli M. 2009. Long-term erosion of tree reproductive trait diversity in edge-dominated Atlantic forest fragments. *Biol. Conserv.* 142:1154–65
193. Groeneveld J, Alves LF, Bernacci LC, Catharino ELM, Knogge C, et al. 2009. The impact of fragmentation and density regulation on forest succession in the Atlantic rain forest. *Ecol. Model.* 220:2450–59
194. Pütz S, Groeneveld J, Alves LF, Metzger JP, Huth A. 2011. Fragmentation drives tropical forest fragments to early successional states: a modelling study for Brazilian Atlantic forests. *Ecol. Model.* 222:1986–97
195. Thompson I. 2011. Biodiversity, ecosystem thresholds, resilience and forest degradation. *Unasylva* 62:25–30
196. Bonner MTL, Schmidt S, Shoo LP. 2013. A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations. *For. Ecol. Manag.* 291:73–86
197. Johnson DL, Ambrose SH, Bassett TJ, Bowen ML, Crummey DE, et al. 1997. Meanings of environmental terms. *J. Environ. Qual.* 26:581–89
198. Penman J, Gytarsky M, Hiraishi T, Krug T, Kruger D, et al., eds. 2003. *Definitions and methodological options to inventory emissions from direct human-induced degradation of forests and devegetation of other vegetation types*. Rep., Inst. Glob. Environ. Strateg., Int. Panel Clim. Change, Geneva
199. Hobley M. 2005. The impacts of degradation and forest loss on human well-being and its social and political relevance for restoration. In *Forest Restoration in Landscapes: Beyond Planting Trees*, ed. S Mansourian, D Vallauri, N Dudley, pp. 22–30. Berlin, Ger.: Springer
200. Howell EA, Harrington JA, Glass SB. 2012. *Introduction to Restoration Ecology*. Washington, DC: Island
201. Van Andel J, Aronson J. 2012. *Restoration Ecology: The New Frontier*. Oxford, UK: Blackwell
202. Clewell AF, Aronson J. 2013. *Ecological Restoration: Principles, Values and Structure of an Emerging Profession*. Washington, DC: Island
203. Stanturf JA. 2015. Future landscapes: opportunities and challenges. *New For.* 46:615–44

Annual Review of
Environment
and Resources

Volume 42, 2017

Contents

I. Integrative Themes and Emerging Concerns

II. Earth's Life Support Systems

III. Human Use of the Environment and Resources

IV. Management and Governance of Resources and Environment

V. Methods and Indicators

Indexes

Errata

An online log of corrections to *Annual Review of Environment and Resources* articles may be found at http://www.annualreviews.org/errata/environ