Supporting Information file to the manuscript

"Explore Before You Restore: Incorporating Complex Systems thinking in Ecosystem Restoration"

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Appendix S1 Extended Glossary.

Table 1 Eight properties of complex systems (after Filotas et al., 2014).

Heterogeneity: Existence of interacting components whose global dynamics cannot be calculated by summing the dynamics of individual components.
Hierarchy: Elements at different levels interact to form an architecture that characterizes the system.
Self-organization: Local interactions among a system's components cause coherent patterns, entities, or behaviors to emerge at higher scales of the hierarchy, which in turn affect the original components through feedbacks.
Openness: Energy, matter, and information are exchanged with the external environment through porous system boundaries.
Adaptation: Adjustments in the behavior and attributes of a complex system in response to changes in external inputs.
Memory: Information from the past influences future trajectories through persistent change in the system's structure and composition.
Nonlinearity: Sensitivity to initial conditions exists so that small differences are amplified and lead to divergent trajectories.
Uncertainty: The dynamics of complex systems are riddled with various sources of uncertainty, which challenges predictions about future regimes.

Table 2 Complex Systems (Carpenter et al., 2011; Carpenter et al., 2012; Folke et al., 2010; Nikinmaa, 2020; Scheffer et al., 2012)

Alternative stable state (ASS): Alternative combinations of ecosystem regimes and environmental conditions that may form and persist at a particular spatial extent and temporal scale.
Basin of attraction: A set of system variable and parameter values in which every point will eventually gravitate back to the attractor after being disturbed. A disturbance can move the system from one basin to another and cross a threshold during the process.
Critical slowdown (CSD): Ecosystems recover more slowly from disturbances in the vicinity of tipping points, which is generally indicated by a rise in temporal correlation and variance.
Resilience: The degree, manner, and pace of recovery of ecosystem properties after natural or human disturbance.
a) **Engineering resilience**: The time it takes for variables to return to their pre-disturbance equilibrium following a disturbance. It encompasses recovery of the system and assumes a single equilibrium regime.
b) **Ecological resilience**: A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain within critical thresholds or the same regime. It encompasses resistance and recovery of the system and assumes multiple equilibria regimes.
c) **Social-ecological resilience** (or **Resilience thinking**): The capacity of a social-ecological system to continually change and withstand disturbances yet remaining within critical thresholds or the same regime, i.e., essentially maintaining its structure and functions. It encompasses resistance, recovery, adaptive capacity and ability to transform the system and assumes multiple equilibria regimes.

Appendix S2 Problem statement. We tested whether there was a lack of inclusion of Complex Systems concepts in restoration guidance by scanning 13 guidelines documents on ecosystem restoration from leading international organizations (FAO, GPFLR, ICRAF, ITTO, IUCN, IUFRO, RBGKew, SER, and WRI) published in the last decade 2012-2022 (**Table 1**). We performed a word count of keywords related to Regime shifts, Resilience, and Ecological feedbacks. We also examined these documents for their meaning of 'resilience' (**Table 2**), i.e. whether 'resilience' was included as *general* or *specific r*esilience, i.e. resilience to all kinds of shocks/stressors or, respectively resilience of a specific ecosystem component and to a specific stressor.

Table 1 Complex Systems concepts: word use in international restoration guidelines (See citations in Table 2).

			Regime shifts									Ecological Resilience				Ecological Feedbacks
Title	**Organization**	**Year**	ASS[a]	Alternative ecosystem	Regime shift	(Critical) threshold	Tipping/ Turning point	CSD[b]	EWS[c]	Basin of attraction	Hyster-esis	Resilience	Engin[d]	Ecolog[e]	Soc-Ecol[f]	Feedback Feed back
Global Guidelines for the Restoration of Degraded Forests and Landscapes in Drylands	FAO	2015	0	0	0	2	0	0	0	0	0	60	0	1	1	2
Restoring forest landscapes through assisted natural regeneration: a practical manual	FAO	2019	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Principles for ecosystem restoration to guide the United Nations decade 2021-2030	FAO	2021	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Restoring forest and landscapes: the key to a sustainable future	GPFLR	2018	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Practitioner's field guide: agroforestry for climate resilience	ICRAF	2020	0	0	0	0	0	0	0	0	0	84	0	0	0	0
From Tree Planting to Tree Growing: Rethinking Ecosystem Restoration Through Trees	ICRAF	2020	0	0	0	0	0	0	0	0	0	3	0	0	0	0
Guidelines for Forest Landscape Restoration in the Tropics	ITTO	2020	0	0	0	1	0	0	0	0	0	37	0	1	0	0
Biodiversity guidelines for forest landscape restoration opportunities assessments	IUCN	2018	0	0	0	0	0	0	0	0	0	18	0	1	0	0
Implementing Forest Landscape Restoration: A practitioner's Guide	IUFRO	2017	0	0	0	2	0	0	0	0	0	23	0	2	0	0
Kew declaration on reforestation for biodiversity, carbon capture and livelihoods	Royal Botanic Gardens Kew	2021	0	0	0	0	0	0	0	0	0	2	0	0	0	0
International principles and standards for the practice of ecological restoration, 2nd edition	SER	2019	0	2	0	4	0	0	0	0	0	34	0	3	4	2
The Restoration Diagnostic	WRI	2015	0	0	0	0	0	0	0	0	0	14	0	0	0	0
Scaling up Regreening: Six steps to success	WRI	2015	0	0	0	0	0	0	0	0	0	17	0	0	0	0
Across all 13 documents			**0**	**2**	**0**	**9**	**0**	**0**	**0**	**0**	**0**	**298**	**0**	**8**	**5**	**4**

[a]Alternative Stable regime(s); [b]Critical slowdown; [c]Early(-)warning signal; [d]Engineering resilience; [e]Ecological resilience; [f]Social(-)ecological resilience, Socio(-)ecological resilience

Table 2 The meaning of the Complex Systems concept of 'Resilience' as frequently used in international restoration guidelines. We extracted the paragraphs where the word Resilience was used, to evaluate, for each instance, whether the guidelines referred to General resilience (left column), i.e. resilience of ecosystems to all kinds of shocks/stressors, or to Specific resilience (right column), i.e. resilience of a specific ecosystem component to a specific stressor. See below* for examples.

Title	**Organization**	**Year**	**General:** Resilience of ecosystems to all kinds of shocks/stressors	**Specific:** Resilience **of** an ecosystem component **to** specific stressor
Global Guidelines for the Restoration of Degraded Forests and Landscapes in Drylands (FAO, 2015)	FAO	2015	60	0
Restoring forest landscapes through assisted natural regeneration: a practical manual (FAO, 2019)	FAO	2019	1	0
Principles for ecosystem restoration to guide the United Nations decade 2021-2030 (FAO et al., 2021)	FAO	2021	1	0
Restoring forest and landscapes: the key to a sustainable future (Besseau, Graham, and Christophersen, 2018)	GPFLR	2018	4	0
Practitioner's field guide: agroforestry for climate resilience (Martini et al., 2020)	ICRAF	2020	82	2
From Tree Planting to Tree Growing: Rethinking Ecosystem Restoration Through Trees (Duguma et al., 2020)	ICRAF	2020	3	0
Guidelines for Forest Landscape Restoration in the Tropics	ITTO	2020	37	0
Biodiversity guidelines for forest landscape restoration opportunities assessments (Beatty et al., 2018)	IUCN	2018	18	0
Implementing Forest Landscape Restoration: A practitioner's Guide (Stanturf et al., 2017)	IUFRO	2017	23	0
Kew declaration on reforestation for biodiversity, carbon capture and livelihoods (The Declaration Drafting Committee, 2021)	Royal Botanic Gardens Kew	2021	2	0
International principles and standards for the practice of ecological restoration, 2nd edition (Gann et al., 2019)	SER	2019	33	1
The Restoration Diagnostic (Hanson et al., 2015)	WRI	2015	14	0
Scaling up Regreening: Six steps to success (Reij C. & Winterbottom R., 2015)	WRI	2015	17	0
Across all 13 documents			**295 (99%)**	**3 (1%)**

***Examples** (Dudney et al., 2018; Folke et al., 2010)

General resilience: Resilience to all kinds of shocks/stressors

- **Example from:** SER, 2019, *International principles and standards for the practice of ecological restoration* (Gann et al., 2019).
- **Paragraph:** *Ecological restoration, when implemented effectively and sustainably, contributes to protecting biodiversity; improving human health and wellbeing; increasing food and water security; delivering goods, services, and economic prosperity; and supporting climate change mitigation, **resilience**, and adaptation.*
- **Explanation:** No specification of resilience *of* specific ecosystem components and *to* specific stressors or disturbances in the system. The focus here is on the need for restoration to achieve resilient ecosystems to all kinds of shocks.

Specific resilience: Specific resilience of a system component to specific stressor.

- **Example from:** ICRAF, 2020, *Practitioner's field guide: agroforestry for climate resilience* (Martini et al., 2020).
- **Paragraph:** *At landscape level: more than 20 other households adopted and implemented similar agroforestry practices on their individual land; increased planted forest area in the village by more than 100 ha in total; modified the microclimate; and enhanced landscape **resilience** to increasing temperatures.*
- **Explanation:** Resilience is referred to here (although only partly) as resilience *of* a specific ecosystem component (this part is missing) *to a specific* measurable *stressor* (increasing temperatures).

Appendix S3 Restoration Project Cycle. Although the nomenclature, structure and restoration project steps vary substantially depending on goal, scale, budget, and organization, we identified six recurrent phases in project cycles based on the different phases that are described in 9 key ecosystem restoration guidelines from leading international organizations published in the last decade 2012-2022: **Assessing** (green), **Planning** (including 'Visioning' + 'Conceptualizing' or 'Designing'; orange), Implementing (or 'Acting'; blue), **Monitoring & Evaluation** (or 'Monitoring' or 'M&E'; pink), **Maintaining** (or 'Managing' or 'Sustaining'; grey), and **Adaptive management** (or 'Replan'; purple; cuts across all phases) (see also **Table 3, Figure 1** in main text). All phases are strongly interconnected as part of an iterative process. Hence, they are not necessarily sequential. E.g., although the bulk of *M&E* occurs after *Implementation*, activities critical to *M&E* begin beforehand because of the need to design monitoring plans, develop budgets, collect pre-implementation data etc. Adaptive management cuts across all other phases, i.e. feedbacks at regular intervals in the cycle exist, where, depending on changing conditions, or on new information gained throughout *implementation*, priorities and *planning* may continuously shift (Gann et al., 2019; ITTO, 2020).

Title	Organization	Year	Phases				
			Assessing	Planning	Implementing	M&E	Maintaining
			Adaptive management				
Global Guidelines for the Restoration of Degraded Forests and Landscapes in Drylands	FAO	2015		Planning	Implementing	Monitoring & Evaluating	
Principles for ecosystem restoration to guide the United Nations decade 2021-2030	FAO	2021		Planning	Implementation	Monitoring & Evaluating	
				Adaptive management			
Restoration team's field guide: agroforestry for climate resilience	ICRAF	2020		Plan	Act	Monitor	
				Replan			
Guidelines for Forest Landscape Restoration in the Tropics	ITTO	2020		Visioning + Conceptualizing	Acting/ Implementing		Sustaining
				Monitoring and Adaptive management			
Biodiversity guidelines for forest landscape restoration opportunities assessments	IUCN	2018	Assessment		Implementation	Monitoring	
Implementing Forest Landscape Restoration: A restoration team's Guide	IUFRO	2017		Conceptualizing + Designing	Implementing	Monitoring	
International principles and standards for the practice of ecological restoration 2nd edition	SER	2019		Planning and Design (incl. Assessment)	Implementation	Monitoring & Evaluating	Maintaining
				Adaptive management			
The Restoration Diagnostic	WRI	2015		Design	Implement	Monitor	
WWF-SER Standards for the certification of forest ecosystem restoration projects (WWF & SER, 2022)	WWF-SER	2022		Planning and Design (including Assessment)	Execution	Monitoring & Evaluation (incl. Reports, Information management)	Aftercare and long-term Maintenance

During the **Assessing** phase, i) the drivers, intensity, and extent of degradation, as well as the pre-degradation historic regime, ii) the expected impacts of climate change, iii) the local and regional socio-economic context and iv) reciprocal engagement of local stakeholders are assessed (**Table 3**). During the **Planning** phase, i) short-term, measurable objectives as well as longer-term goals (i.e. 'Visioning), and ii) suitable restoration measures (i.e. 'Conceptualizing' or 'Designing') are defined along with iii) suitable key performance indicators (KPIs) to track restoration performance (FAO et al., 2021). These measures are then performed in the **Implementing** phase and range from; i) actions to reduce or eliminate degradation, to ii) additional interventions needed to assist recovery such as re-establishing disturbance regimes, restoring physical conditions, removing specific species, facilitating regeneration, adding seeds/species, excluding herbivores etc. (Chazdon, 2008; Poorter et al., 2016; Stanturf et al., 2017; Suding et al., 2004) (Chazdon, 2008; Chazdon et al., 2021; Stanturf et al., 2017; Suding et al., 2004). During **M&E**, restoration performance is tracked by measuring KPIs, which permits evaluation of whether the objectives are being met, and whether constraints remain. Usually, this phase will also include documentation and reporting of project aims and results, and future recommendations to maintain or achieve objectives. Next, once the objectives are met, emphasis shifts from evaluating to maintaining the objectives, and the cycle moves into the **Maintaining** phase (ITTO, 2020; Reij & Winterbottom, 2015; Suding et al., 2004). Finally, some guidelines include an additional phase of **Adaptive management** which cuts across all phases, i.e. at regular intervals in the cycle; i) the objectives are re-evaluated, and ii) the cycle is reiterated to other phases of the project cycle (FAO et al., 2021; Gann et al., 2019; ITTO, 2020; Lynch et al., 2022; Zabin et al., 2022).

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