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LEARNING FROM NON-LINEAR ECOSYSTEM DYNAMICS IS VITAL FOR ACHIEVING LAND DEGRADATION NEUTRALITY

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ABSTRACT

Land Degradation Neutrality is one of the Sustainable Development Goal targets, requiring on-going degradation to be balanced by restoration and sustainable land management. However, restoration and efforts to prevent degradation have often failed to deliver expected benefits, despite enormous investments. Better acknowledging the close relationships between climate, land management and non-linear ecosystem dynamics can help restoration activities to meet their intended goals, while supporting climate change adaptation and mitigation. This paper is the first to link ecological theory of non-linear ecosystem dynamics to Land Degradation Neutrality offering essential insights into appropriate timings, climate-induced windows of opportunities and risks and the financial viability of investments. These novel insights are pre-requisites for meaningful operationalisation and monitoring of progress towards Land Degradation Neutrality. © 2017 The Authors. Journal of Land Degradation & Development published by John Wiley & Sons Ltd.

KEY WORDS: sustainable land management; ecosystem regime; timing; cost–benefit; window of opportunity and risk

LAND DEGRADATION NEUTRALITY AT THE FRONTLINE

Political momentum to tackle the adverse impacts of land degradation is high, supported by strong global acknowledgement that land degradation can have negative impacts for both climate change and biodiversity (Reed & Stringer, 2016). In 2015, the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) started its Thematic Assessment on Land Degradation and Restoration; it also marked the mid-point in the International Decade of Deserts and Desertification as well as being the International Year of Soils. The biggest political boost for addressing land degradation came from the United Nations General Assembly's adoption of the Sustainable Development Goals (SDGs), particularly SDG target 15.3: '*By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world*'. This formally introduced the idea of Land Degradation Neutrality (LDN) into global sustainability planning.

LDN refers to a state of zero net land degradation, where 'the amount and quality of land resources necessary to support ecosystem functions and services and enhance food security remain stable or increase within specified temporal and spatial scales and ecosystems' (UNCCD, 2016). LDN therefore balances degradation with maintenance and improvement of the land's condition through restoration and sustainable land management (SLM) practices, on-site or off-site (Barkemeyer *et al.,* 2015). Restoration implies an ecosystem's return from a degraded to a functional state, while SLM practices aim to prevent the loss of ecosystem functioning and even further improve an ecosystem's functionality. SLM increases an ecosystem's resilience defined as the degree of disturbance it can withstand while remaining within critical thresholds, thus maintaining its core structure and functioning (Holling, 1973). In considering LDN, off-site impacts can be important to either stress that degradation and improvement need not be balanced at the same spot, or that degradation or improvement actions have (positive or negative) impacts beyond the location where they occur, for example, upstream soil conservation may lead to downstream water shortage and/or reduced flood damage.

Achieving LDN also underpins the accomplishment of several of the other SDGs, including SDG 13 on climate action and efforts to tackle other challenges such as poverty alleviation, food, water and energy security, human health, migration, conflict and biodiversity loss (Akhtar-Schuster *et al.,* 2017). How LDN can be operationalised is currently considered in the work programme of the United Nations Convention to Combat Desertification (UNCCD)'s Science-Policy Interface (SPI) (Orr *et al.,* 2017). The SPI recognises that while LDN is an international policy target, aggregate efforts at smaller scales enable progress. Indeed, countries at the 2015 UNCCD Conference of the Parties agreed to set voluntary LDN targets, acknowledging that 'striving to achieve SDG target 15.3 is a strong vehicle for driving the implementation of the UNCCD' (UNCCD, 2015; Decision 3).

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National level target-setting means that decisions will be needed on where and when best to invest in SLM and restoration, depending on the types and status of land degradation in each country. This presents a need for cost-effective decision making and a deeper understanding of the costs of inaction as well as the costs of different types of action. The recent Economics of Land Degradation (ELD) Initiative report *The Value of Land* provided a new evidence base that partly addresses this need (ELD, 2015). The ELD report has helped policy makers to better appreciate that globally misuse of vegetation, soils and water has undermined the land's capacity to maintain healthy ecosystems and to provide important ecosystem services, and that this bears a significant cost (ELD, 2015). However, land degradation cannot be easily decreased everywhere at acceptable cost: location-specific factors determine costs and success. This requires local socio-ecological causal factors and their interlinkages with broader contextual conditions to be well understood for interventions to be effective (Suding, 2011; Wilson *et al.,* 2011; Diffenbaugh & Field, 2013). Moreover, land degradation and climate change are closely linked phenomena. Widespread land degradation is both a driver and consequence of climate change (Reed & Stringer, 2016). Degradation can cause stored carbon to be released while also reducing adaptation options and eroding biodiversity. Higher atmospheric greenhouse gas concentrations will increase future climate variability, including more extreme droughts and peak rainfall, potentially driving even more severe degradation and limiting adaptation even further.

While existing scientific knowledge and practical implementation skills can clearly support LDN operationalisation (Chasek *et al.,* 2015; Stavi & Lal, 2015), decision makers lack evidence that can guide them on where and when best to invest in restorative and preventive actions. Even the official definition of LDN refers only to neutrality over 'specified temporal and spatial scales' (UNCCD, 2016). Decision making requires an understanding of key non-linear ecosystem dynamics including critical thresholds, which ecosystems often, but not always, exhibit (Suding & Hobbs, 2009). This is particularly important in addressing the restoration aspect of LDN, which until recently was rather neglected under the UNCCD. By applying principles from ecological theory of non-linear ecosystem dynamics, it is possible to inform appropriate investments in recovering and sustaining ecosystems. It is therefore vital that approaches are identified that bring together decision makers' knowledge needs and insights into non-linear ecosystems' behaviour to inform cost-effective and efficient progress towards LDN. In this paper, we present the first demonstration of the utility of considering non-linear ecosystem dynamics to provide essential insights into appropriate timings, climate-induced windows of opportunities and risks, and the financial viability of investments in LDN. In linking non-linear ecosystem behaviour to an economic evaluation of land management options, we identify opportunities and challenges for cost-efficiently moving towards the LDN target.

GUIDING LAND MANAGEMENT THROUGH A PERSPECTIVE ON NON-LINEAR ECOSYSTEM DYNAMICS

Widespread failure in ecosystem restoration and degradation prevention, even with massive investments, has underpinned the broad agreement that ecosystems can behave in complex, non-linear ways (Westoby *et al.,* 1989; Scheffer *et al.,* 2001). In contrast to gradual responses, several studies demonstrate that a range of terrestrial and aquatic ecosystems exhibit alternative dynamic regimes and threshold dynamics (Scheffer & Carpenter, 2003; Folke *et al.,* 2004; Hirota *et al.,* 2011; Suding, 2011). Restoration of ecosystem performance after a decline and prevention of degradation can require considerably stronger efforts in non-linear than in gradually responding systems but can also benefit from particular opportunities due to non-linear dynamics. Hence, recognition of dynamic ecosystem regimes and threshold dynamics can provide crucial advances to operationalising LDN.

A dynamic ecosystem regime is a region in a state space – also called a basin of attraction – in which an ecosystem develops towards a stable equilibrium (Scheffer *et al.,* 2001). Small disturbances or management impacts can change an ecosystem's state, but the system remains within a given regime and ultimately tends towards the stable equilibrium due to positive internal feedbacks. Dynamic regimes are separated by thresholds defined as boundaries in time and space. At a threshold, a small change in environmental conditions, such as precipitation variability, herbivore pressure or fire frequency, trigger a large change in ecosystem state, implying abrupt shifts from one dynamic regime to another. Existence of two alternative dynamic regimes under the same environmental conditions implies hysteresis (Figure 1 a) such that a system's degradation path can strongly differ from its restoration path. Severe disturbances or large management impacts can shift the system over the border of a basin of attraction to an alternative basin of attraction. Changes in environmental conditions exceeding a threshold (T_1 and T_2 in Figure 1a) can also trigger a regime shift. Responses manifest as alterations in the productivity and cover of grasses, shrubs or trees and species composition as well as other ecosystem state variables. Such alterations can demand minor or major investments in order that they may be avoided, reduced and/or reversed.

A grass-dominated and a shrub-dominated landscape can be considered as two alternative regimes, which are useful to illustrate shifts in internal feedbacks. Intense livestock grazing can drive degradation shifts from grassland (healthy state) to shrubland (degraded state), leading to decreased fuel connectivity and lack of fire disturbance (Friedel, 1991). Without fire, germinating shrubs that are not grazed can survive and outcompete grasses. Under significantly changed feedback mechanisms governed by grass–shrub competition, shrubs can persist even after grazing pressure reductions. Land management needs to reduce grazing intensity in order to improve environmental conditions well

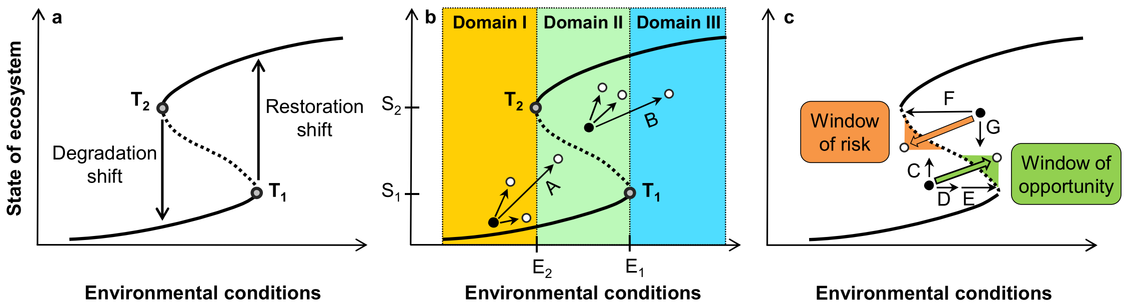

Figure 1. Non-linear dynamics: Dynamic ecosystem regimes and priority situations for LDN interventions (Figure 1a adapted from Scheffer *et al.,* 2001). (Note: Environmental conditions capture, for example, increase in precipitation or reduction in herbivory and fire frequency. Ecosystem state variables encompass, for example, vegetation cover, density and diversity. Bold lines represent stable equilibria; dotted lines unstable equilibria (borders between basins of attraction). Black dots indicate an ecosystem's current state; white dots show possible management-induced and climate-induced changes. Figure 1a shows hysteresis including critical thresholds T_1 and T_2 that distinguish degradation and restoration pathways. Figure 1b depicts stability domains. The bi-stable Domain II represents priority situations for restorative and preventive actions. Rightward pointing arrows show land management effects. Movement along arrow A = ecosystem enters bi-stable domain; movement along arrow B = ecosystem leaves bi-stable domain. Figure 1c illustrates windows of opportunities and risks. Arrows exemplify effects of different types of management practices and external climate drivers: C = seeding, D = reduced grazing pressure, E = extremely wet episode, F = drought and G = deforestation.). [Colour figure can be viewed at wileyonlinelibrary.com]

beyond the pre-degradation threshold at which the ecosystem shifted to the alternative regime (T_2 in Figure 1a) for the grass-dominated regime to recover. This demonstrates that under hysteresis, ecosystem restoration may require greater efforts and investments compared with a non-hysteretic ecosystem. Changes in environmental conditions may alter regime boundaries, and hence, the size of a basin of attraction affecting its resilience to disturbance. An increase in basin size can reduce the probability of a regime shift, as the system is less easily driven over a threshold into an alternative regime, implying greater resilience. Likewise, preventive actions such as livestock rotation to reduce grazing pressure are crucial when a healthy grassland approaches a threshold (T_2 in Figure 1a). By increasing the distance to a threshold, this can reduce the likelihood of a shift to the degraded shrub-dominated regime.

As ecosystems are complex systems displaying high variability in constituting processes and states, there is no single one-dimensional threshold that determines restoration or degradation outcomes. Underlying processes must therefore be adequately captured in threshold models to avoid misinterpretation of conditions under which ecosystems may not be restorable because a historical reference cannot be re-established (Bestelmeyer, 2006). Recent work on 'novel ecosystems' highlights the necessity of distinguishing situations in which original states cannot be restored, for example, due to constraining interactions between climate change and land use (Hobbs *et al.,* 2013). Land management considering diverse ecosystem functions and multi-dimensional thresholds is a pre-requisite to achieve LDN.

An ecosystem's state relative to critical thresholds can provide key insights into appropriate timings and urgency of restorative and preventive interventions. Ecosystems in a bi-stable situation (Domain II in Figure 1b) must be prioritised. Experimental evidence shows that arid grasslands in the Southwestern United States that degraded to shrub-dominated ecosystems due to intensive grazing can be restored when livestock are excluded (Valone *et al.,* 2002). In the dynamic regime perspective, livestock exclosure induced improved environmental conditions, up to or beyond E_1 (Figure 1b), enabling a restoration shift. However, shrub-dominated systems may respond slowly to livestock removal as a single management strategy, requiring >20 years before natural grasslands regenerate (Valone *et al.,* 2002). These time lags create delays before management effects materialise highlighting that restoration efforts often require a long-term vision and commitment to be successful.

In a domain with a single degraded regime, such as bare soil (Domain I in Figure 1b), land management principally cannot induce a shift to the healthy (e.g. vegetated) regime due to the absence of an alternative regime. Yet, management such as reduction in grazing pressure and erosion control (especially in regions with erodible soils, highly variable and intensive rainfall and strong winds) is required as complete abandonment may prompt irreversible degradation. For example, bush encroachment and repeated wildfires affecting abandoned landscapes are known to lead to long-term loss of productivity (Roques *et al.,* 2001; Hill *et al.,* 2008) and the high cost of reversing such degradation is prohibitive (Reed *et al.,* 2015). Similarly, an ecosystem in Domain III cannot shift to an alternative regime, even with a severe disturbance. Here, land management would ideally maintain environmental conditions beyond E_1 (Figure 1b), avoiding the possibility of a regime shift.

IDENTIFYING CLIMATE-DEPENDENT WINDOWS OF OPPORTUNITIES AND RISKS

Environmental conditions can strongly vary, opening windows of opportunities and risks for restoration and degradation prevention. Opportunities include exceptionally wet episodes, such as those associated with the El Niño Southern Oscillation (Holmgren & Scheffer, 2001). Field monitoring and remotely-sensed estimates of tree cover demonstrate that seeding (arrow C in Figure 1c) and protecting seedlings from herbivores (arrow D in Figure 1c) at the onset of a rainy El Niño episode (arrow E in Figure 1c) facilitated tree recruitment and regeneration of extensive dry forests in coastal Peru (Sitters *et al.,* 2012). This fine-tuned dual management strategy was particularly successful in wetter low-lying areas and sandy soils. In contrast to seeding as a single restoration strategy, which was insufficient to induce forest restoration (Sitters *et al.,* 2012), this combination can trigger the passage of thresholds, inducing sudden, long-lasting restoration shifts towards a high vegetation cover regime (green arrow in Figure 1c). These dual management strategies together with more frequent extreme precipitation events associated with future climate change may generate important windows of opportunities for the recovery of dry forests in some coastal regions in western South America (Holmgren *et al.,* 2013) upon which people's livelihoods rely. Benefitting from such opportunities however requires efficient flood and erosion control measures to avoid land degradation.

Land management to prevent degradation shifts must consider windows of risks when typical degradation drivers, such as drought and deforestation, interactively affect an ecosystem's state. For example, dynamic modelling suggests that combined drought and deforestation can result in more widespread shifts from rainforest to savanna regimes in the south-eastern Amazon basin than those triggered by either drought or deforestation (orange arrow in Figure 1c; Staal *et al.,* 2015). Here, both drought and deforestation favour grass invasion that increases flammability, decreasing the rainforest's fire resilience and therefore increasing the probability of a degradation shift to a savanna regime. As the combined effects of drought and deforestation can move a forest out of Domain III into the bi-stable Domain II (Figure 1b), land management is required to stabilise internal feedbacks (e.g. preventing fragmentation of forest canopy and grass invasion) in order to reduce the probability of a degradation shift. This underlines the importance of policies and mechanisms to prevent deforestation, particularly when future climate change is associated with more frequent and intense droughts (Malhi *et al.,* 2008), and coupled degradation drivers limit the boundaries within which forests can be sustainably managed (Scheffer *et al.,* 2015).

DECIDING WHEN TO INVEST

For financial viability of investments, stability domains (Figure 1b) matter greatly, as does the opening of a climate-dependent window of opportunity or risk (Figure 1 c). Cost–benefit analysis is traditionally applied to assess expected financial impacts of land management interventions (Qadir *et al.,* 2014; Giger *et al.,* 2015; Baptista *et al.,* 2016). While the feasibility of interventions may depend on a variety of criteria, a major assumption is that a land manager would invest only in those measures whose expected returns are positive. It is however often difficult to anticipate the effects of land management with certainty (Suding, 2011; Wilson *et al.,* 2011; Nilsson *et al.,* 2015).

A global meta-analysis of ecosystem restoration depicts large variations in benefit–cost ratios across a range of biomes including grasslands, forests and wetlands (De Groot *et al.,* 2013). Similarly, a global analysis of successful SLM cases reveals great differences in the costs and benefits that stakeholders perceived in establishing and maintaining SLM measures depending on management type, region and area size (Giger *et al.,* 2015). Further differentiation of costs and benefits according to varying degradation levels, environmental conditions and climate risks and opportunities is essential to inform investment decisions. Clearly, a better understanding of dynamic ecosystem regimes can advance decision making on investment in land management, particularly concerning large-scale restoration and SLM programmes. Here, timing is a key factor: investment costs are required immediately and maintenance costs may pose an additional strain on resources in the initial years following an investment, whereas the later the benefits are anticipated to occur, the less they are valued at the time of outlay. In cost–benefit analysis, this is captured through discounting of future costs and benefits. In the following paragraphs, we discuss the effects and cost-effectiveness of seeding as a key restoration measure to illustrate major differences in the costs and benefits arising from action across the stability domains. Seeding makes for a good illustrative case as it directly affects an ecosystem's state, and its success may vary with environmental conditions. Other restoration measures such as fencing off degraded land can be cheaper and equally effective but do not affect an ecosystem's state directly.

Considering a degraded ecosystem in a bi-stable domain (Domain II in Figure 1b), a priority situation for restoration, investments coinciding with a window of opportunity have greater chances of succeeding and generating higher gross benefits (green line and area in Figure 2b) than those outside such a window of opportunity. This also raises chances of a positive return on investment. Insights from germination biology can support the evaluation of soil moisture and weather conditions, especially in regions with a highly variable and changing climate (Broadhurst *et al.,* 2016). When seeding and improved environmental conditions are insufficient for the system to cross a threshold, recurrent costs to maintain the achieved improvement and prevent a degradation tendency are incurred while waiting for a new window of opportunity (see plateau in green line and repeated sharp decline in grey line during early years in Figure 2b). Once an ecosystem has passed a critical threshold during a new window of opportunity, vegetation cover increases naturally without any further maintenance costs (increase in green and grey lines and areas in Figure 2b).

In contrast, improving a severely degraded ecosystem under adverse environmental conditions (Domain I in Figure 1 b) is expensive and takes longer to materialise (grey line and area in Figure 2a). Here, we illustrate a case in which site preparation did not immediately result in vegetation improvement but disturbed the existing vegetation and led to an initial decline in vegetation cover. This decline implies

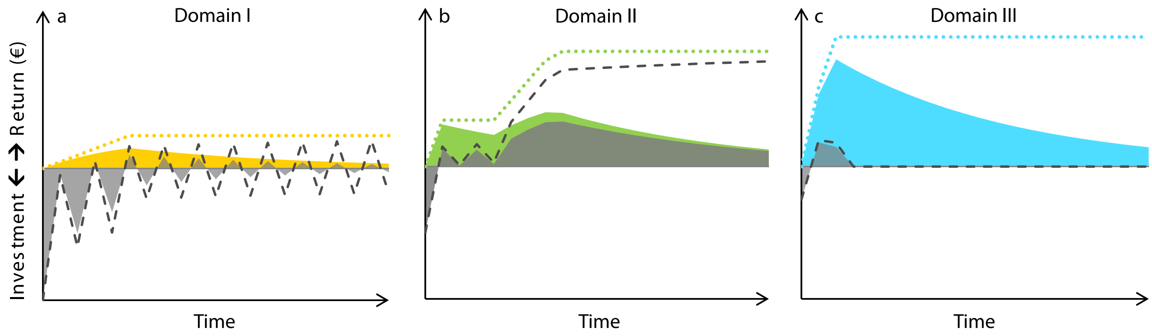

Figure 2. Cost-efficiency of management interventions dependent on stability domains (Figure 1b) and window of opportunity (Figure 1c). Areas represent discounted (present) value of investment costs and benefits, while lines represent future values. Coloured areas refer to gross present benefits. Grey areas refer to net present benefits (i.e. subtracting from gross benefits the intervention costs and any benefits that would have been obtained without the intervention). Coloured lines refer to gross future benefits and grey lines to net future benefits. Gross future benefits depend on productivity levels which vary between stability domains. Figure 2b indicates management effects concurring with a window of opportunity. Note the declining level of initial investment costs and recurrent maintenance costs going from Domain I (Figure 2a) to Domain III (Figure 2c). [Colour figure can be viewed at wileyonlinelibrary.com]

a lack of benefits in the first years even with additional maintenance (see early negative values of grey line and area in Figure 2a). As ecosystems tend to return to the lower stable equilibrium (i.e. degrade) if situated above the lower branch of the hysteresis curve in Domain I, recurrent maintenance costs arise (resulting in repeated sharp decline in grey line in Figure 2a), as in Domain II. In the case depicted in Figure 2a, maintenance costs are exemplified to occur every other year (repeated sharp decline in grey line in Figure 2a) reflecting variability in rainfall and vegetation establishment. However, such investments to sustainably improve a degraded ecosystem may not be economical as shown by both total negative present and future net benefits (grey line and area in Figure 2a).

Investment in a healthy ecosystem that tends to improve naturally (located below the upper branch of the hysteresis curve in Domain III, Figure 1b) can increase the speed of improvement (pronounced slope in light blue line and area in Figure 2c), usually at modest investment cost. Net benefits only arise at an early stage and vanish once the ecosystem would have reached the healthy stable equilibrium without the intervention (grey line and area in Figure 2c). The healthy stable equilibrium that is reached will be the same with and without investment. Here, the acceleration of restoration as the ecosystem develops towards the higher stable equilibrium (healthy regime) needs to be high enough to render investment attractive.

SLM as a preventive measure has in the long run frequently been found to be cheaper than ecosystem restoration (ELD, 2015; Nkonya *et al.,* 2016). However, investment costs need to be considered in conjunction with expected benefits, risk of failure and the passage of thresholds, meaning that higher upfront costs might in the long run be offset by restoration benefits (Zahawi *et al.,* 2014; Gilardelli *et al.,* 2016). Long-term field experiments with controlled management and environmental conditions are crucial to test and refine important ecosystem properties and feedbacks captured in models to advance existing and build new theories and inform decision making (Foster *et al.,* 2016). They are key for improving our often incomplete knowledge about the socio-ecological dynamics that facilitate or constrain the implementation of specific land use strategies (Sietz & Van Dijk, 2015) and evaluating threshold behaviour (Suding & Hobbs, 2009). This is a pre-requisite for land-based management decisions that are well-suited to address heterogeneity in global sustainability challenges such as loss of biosphere integrity, livelihood insecurity and socio-ecological vulnerability (Sietz, 2014; Steffen *et al.,* 2015; Kok *et al.,* 2016).

In the face of ever-present uncertainty, learning through monitoring of key processes and feedbacks, scenario analysis and adaptive management is central for decision making and inherently linked to resilience thinking. Efforts aimed at increasing response diversity may be particularly beneficial to address uncertainty in future disturbances and environmental conditions (Suding & Hobbs, 2009). Response diversity describes the variety and heterogeneity of species, ecological communities and feedbacks but also managerial processes, allowing ecosystems and human flexibility to respond in various ways and prepare for anticipated effects of disturbances and ongoing change. High response diversity enables some system components or functions to persist, recuperate or transform when disturbed, while others may experience damage or vanish. Further, as costs and benefits associated with alternative ecosystem regimes can differ significantly depending on land users' perceptions, demands and expectations (James *et al.,* 2015; Tarrason *et al.,* 2016), stakeholder involvement is paramount in decision making.

CONCLUSIONS

Sustainable Development Goal target 15.3 presents a strong demand for approaches that inform cost-effective and efficient progress towards LDN. Our consideration of dynamic ecosystem regimes appraises actions that both foster restoration of degraded ecosystems and prevent degradation of functioning ecosystems, demonstrating that there is no 'one size fits all' solution. It offers three key lessons in operationalising LDN. First, long-term field experiments are essential to strengthen advances in identifying dynamic ecosystem regimes including a variety of relevant ecosystem properties and developing reliable predictions of site-specific degradation and restoration drivers and outcomes. In particular, we call for probabilistic assessments of current ecosystem states in relation to stability domains and systematic use of early warning signals for predicting regime shifts to advance the spatial balancing of land degradation and recovery for achieving LDN. Second, prediction of windows of opportunities and risks is essential to identify critical land management timings that realise ecological benefits at minimum risk and cost. Improved seasonal weather forecasts and El Niño Southern Oscillation early warnings can provide key information for such predictions, especially if packaged with restoration and SLM advice tailored to land users' needs. Third, successful multi-level LDN planning requires managerial flexibility that allows continuous adaptation of investment decisions, including timing interventions according to existing environmental conditions and critical thresholds in ecosystem trajectories. This is a pre-requisite to rapidly take action once opportunities or risks emerge. These insights from non-linear ecosystem dynamics help to better evaluate the effectiveness of land management options for achieving policy goals, advancing the LDN framework developed by the UNCCD's Science-Policy Interface and setting a positive trajectory for achievement of the Sustainable Development Goals and LDN.

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