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Land in balance: The scientific conceptual framework for Land Degradation Neutrality

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ABSTRACT

The health and productivity of global land resources are declining, while demand for those resources is increasing. The aim of land degradation neutrality (LDN) is to maintain or enhance land-based natural capital and its associated ecosystem services. The Scientific Conceptual Framework for Land Degradation Neutrality has been developed to provide a scientific approach to planning, implementing and monitoring LDN. The Science-Policy Interface of the United Nations Convention to Combat Desertification (UNCCD) led the development of the conceptual framework, drawing in expertise from a diverse range of disciplines.

The LDN conceptual framework focuses on the supporting processes required to deliver LDN, including biophysical and socio-economic aspects, and their interactions. Neutrality implies no net loss of the land-based natural capital relative to a reference state, or baseline. Planning for neutrality involves projecting the likely cumulative impacts of land use and land management decisions, then counterbalancing anticipated losses with measures to achieve equivalent gains. Counterbalancing should occur only within individual land types, distinguished by *land potential*, to ensure "like for like" exchanges. Actions to achieve LDN include sustainable land management (SLM) practices that avoid or reduce degradation, coupled with efforts to reverse degradation through restoration or rehabilitation of degraded land. The response hierarchy of *Avoid* > *Reduce* > *Reverse land degradation* articulates the priorities in planning LDN interventions. The implementation of LDN is managed at the landscape level through integrated land use planning, while achievement is assessed at national level.

Monitoring LDN status involves quantifying the balance between the area of gains (significant positive changes in LDN indicators) and area of losses (significant negative changes in LDN indicators), within each land type across the landscape. The LDN indicators (and associated metrics) are land cover (physical land cover class), land productivity (net primary productivity, NPP) and carbon stocks (soil organic carbon (SOC) stocks).

The LDN conceptual framework comprises five modules: A: Vision of LDN describes the intended outcome of LDN; B: Frame of Reference clarifies the LDN baseline; C: Mechanism for Neutrality explains the counterbalancing mechanism; D: Achieving Neutrality presents the theory of change (logic model) articulating the

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impact pathway; and E: Monitoring Neutrality presents the LDN indicators. Principles that govern application of the framework provide flexibility while reducing risk of unintended outcomes.

1. Introduction

Land resources provide food and materials, and the often-overlooked regulating and supporting ecosystem services on which the provisioning services depend (MA, 2005). Demands on global land resources are increasing as the world's population increases in number and affluence, yet the health and productivity of land is deteriorating (Montanarella et al., 2016) and prime agricultural land is being lost to urbanization. Increased competition for land resources will increase social and political instability, exacerbating food insecurity, poverty, conflict and migration (UN-Habitat-GLTN, 2016). It is critical that land degradation is effectively addressed. Management of land degradation will have co-benefits for climate change mitigation and adaptation, and biodiversity conservation, in addition to enhancing food security and sustainable livelihoods (Cowie et al., 2007).

The concept of land degradation neutrality (LDN) was introduced into the global dialogue to stimulate a more effective policy response to land degradation. LDN was adopted as target for Sustainable Development Goal 15, and building capacity to achieve LDN is a primary goal of the UNCCD (UNCCD, 2016).

LDN is defined as "a state whereby 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). The concept was raised to galvanise effort around a concrete target of "no net loss" and it aims to maintain the world's resource of healthy and productive land through a dual-pronged approach of measures to avoid or reduce land degradation, combined with measures to reverse existing degradation, such that losses are balanced by gains. The LDN target is a global goal and countries have been invited to commit voluntarily to LDN at the national level.

The UNCCD Science-Policy Interface (SPI) (See Supplementary information (SI) Table S1 for abbreviations) was requested by the UNCCD's Conference of the Parties (COP) to develop a scientific "Conceptual Framework for Land Degradation Neutrality" to provide a scientifically-sound basis for understanding and implementing LDN, and to inform the development of practical guidance for pursuing LDN and monitoring progress towards the LDN target. While the scope of the UNCCD is limited to drylands, the LDN conceptual framework is applicable across all land types, land uses, and ecosystem services. LDN will underpin the achievement of multiple SDGs related to food security, environmental protection and the sustainable use of natural resources.

This paper presents the scientific conceptual framework for LDN. It conveys the principles, assumptions and rules surrounding LDN in a structured format, and explains the links between its key components, to inform an evidence-based holistic solution to combating land degradation. Section 2 describes the participatory process adopted to develop the framework, while Sections 3 and 4 present the key elements of the conceptual framework followed by a detailed description of its five modules.

2. Development of the framework

While the concept of LDN may seem simple – requiring actions to reverse degradation in order to balance any future degradation – the means of achieving LDN have not been agreed, and concerns have been raised about its feasibility (e.g. Safriel, 2017). The UNCCD Parties therefore recognised the need for a scientific foundation for LDN. An agreed scientific conceptual framework for LDN should facilitate development of a common understanding of the concept, and serve as a common point of reference for the emerging LDN discourse and various LDN initiatives. Therefore, the LDN conceptual framework is intended to assist countries in implementing strategies to address land degradation and achieve LDN.

The framework was devised through a participatory process of knowledge co-creation that began with a survey targeting a diverse mix of domain experts[2] responding to "thought starter" statements designed to generate initial ideas from a range of disciplinary perspectives (SI, Table S4). On the basis of the survey, the following details were agreed:

(1) The scope of the scientific conceptual framework for LDN should include socio-economic as well as biophysical aspects. It should include a conceptual system model, and also describe the application of the model to implement and monitor LDN, and governance of LDN.
(2) Development of the framework should be guided by an agreed Theory of Change (Weiss, 1995) for LDN.
(3) Resilience concepts (Connell et al., 2016, 2015; Connell et al., 2016, 2015) should inform the framework, recognising that LDN interventions must be resilient to deliver LDN and effectively manage land degradation over the long term.

The development of the framework continued with a "writeshop" of the interdisciplinary expert group of authors, to agree on the elements of the framework, and subsequent drafting of the report. The draft was reviewed by eight international experts with expertise in land degradation science, the science-policy interface, and the needs of UNCCD parties.

3. Key elements of the scientific conceptual framework for LDN

LDN is a novel approach to address land degradation. It acknowledges that the land system will be affected by global environmental change and, hence, the framework encourages adaptive management during planning, implementation, monitoring and interpretation of LDN. The framework is structured around the counterbalancing mechanism to achieve neutrality, which projects and seeks to balance anticipated positive and negative changes (Fig. 1). The framework comprises five interconnected modules:

- **Module A** documents the **vision and objectives** of LDN;
- **Module B** explains the LDN **frame of reference,** that is, the baseline against which neutrality is assessed;
- **Module C** establishes the **mechanism for neutrality** (the counterbalancing mechanism);
- **Module D** presents the elements necessary to **achieve LDN**, including the theory of change (logic model), which articulates the pathway for implementing LDN, preparatory assessments and enabling policies, learning and governance;
- **Module E** details the process for **monitoring LDN**, including quantifying, verifying and interpreting the LDN indicators.

Key terms and concepts are defined in the Glossary (SI, Table S2). Principles are provided to guide the implementation of LDN, enabling context-specific adjustments while avoiding perverse outcomes

[2] The initial survey targeted an interdisciplinary team of international experts, SPI members and the UNCCD's Science, Technology and Implementation unit, including the authors of this article.

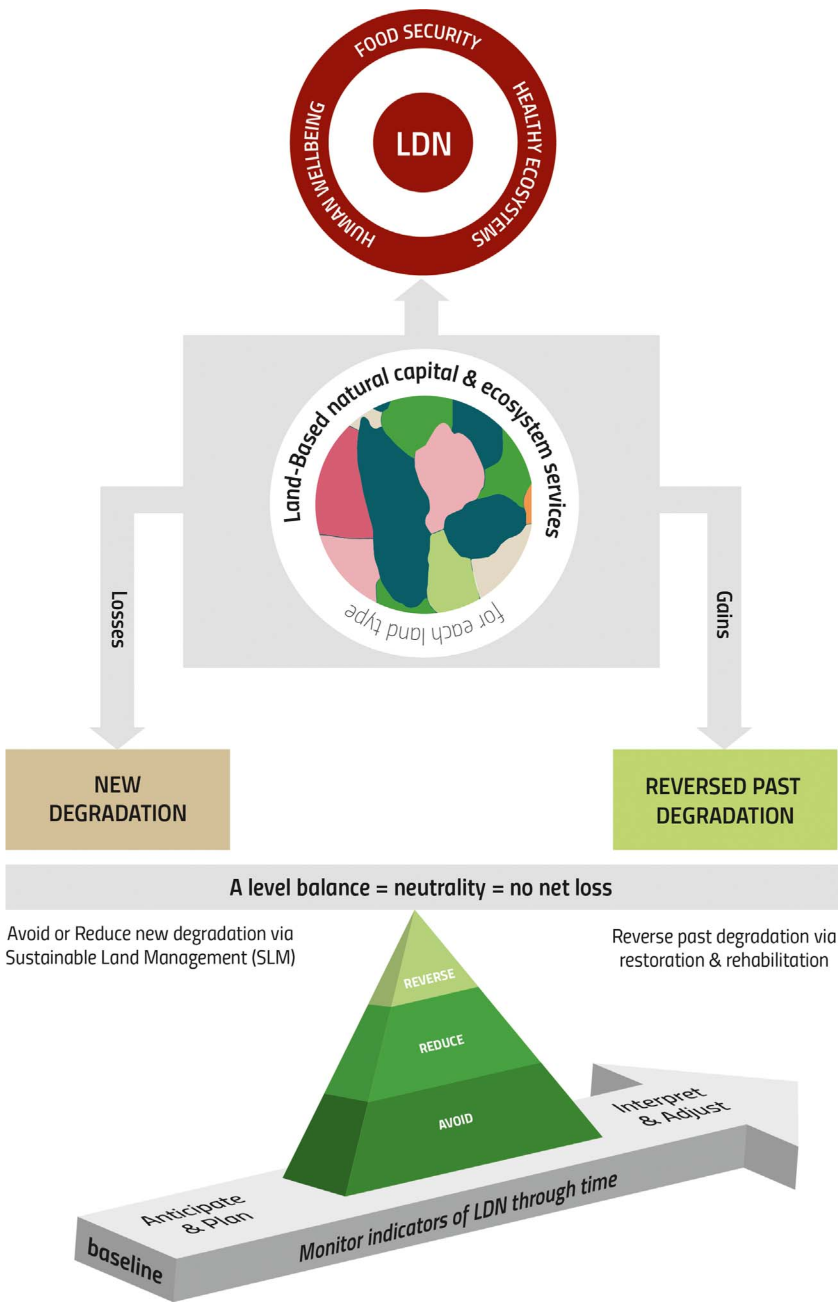

Fig. 1. Schematic of the scientific conceptual framework for land degradation neutrality.

(summarised in Table 1, provided in full in SI, Table S3).

3.1. Module A: The vision of LDN

Module A describes the vision, objectives, causal framework and interlinkages between land-based natural capital and ecosystem services.

3.1.1. The goal and objectives of land degradation neutrality (LDN)

Achieving the state of LDN requires that the land-based natural capital is maintained or enhanced. Thus, the aspirational goal of LDN is to sustain and improve the stocks of land-based natural capital and the associated flows of ecosystem services, to support the future prosperity of humankind. This vision is underpinned by the following objectives:

1. Maintain or improve the sustainable delivery of ecosystem services, from natural and managed ecosystems. This includes maintaining or improving productivity of land to enhance food security, and increasing resilience of land systems and populations dependent on them;
2. Seek synergies with other social, economic and environmental objectives through coherence between policies and measures that address separate environmental and development objectives, and;
3. Reinforce responsible and inclusive governance of land. Govern land for the benefit of all, with emphasis on protection of land tenure rights of vulnerable and marginalized people.

3.1.2. The LDN causal framework

The LDN causal framework (Fig. 2) illustrates the links between the LDN vision, its governance, and implementation; it shows interactions between natural and social capital, highlighting the relationships and processes that sustain and enhance the resilience of land-based natural capital and deliver human wellbeing (food security, sustainable livelihoods). The causal framework also provides insights for

Table 1
Principles underpinning the implementation of LDN.

1	Maintain or enhance land-based natural capital.
2	Protect the rights of vulnerable and marginalised land users.
3	Set national LDN targets based on national circumstances.
4	For neutrality, the LDN target equals (is the same as) the baseline.
5	Neutrality is the minimum objective: countries may elect to set a more ambitious target.
6	Integrate planning and implementation of LDN into existing land use planning processes.
7	Counterbalance anticipated losses in land-based natural capital with interventions to reverse degradation, to achieve neutrality.
8	Manage counterbalancing at the same scale as land use planning.
9	Counterbalance "like for like" (within the same land type).
10	Seek solutions that provide multiple environmental, economic and social benefits, and minimise trade-offs.
11	Base land use decisions on multi-variable assessments, considering land potential, land condition, resilience, social, cultural and economic factors.
12	Apply the response hierarchy in devising interventions for LDN: Avoid > Reduce > Reverse land degradation.
13	Apply a participatory process: include stakeholders, especially land users, in designing, implementing and monitoring interventions to achieve LDN.
14	Reinforce responsible governance: protect human rights, including tenure rights; develop a review mechanism; and ensure accountability and transparency.
15	Monitor using the three UNCCD land-based global indicators: land cover, land productivity (net primary productivity, NPP) and carbon stocks (soil organic carbon, SOC).
16	Use the "one-out, all-out" approach to interpret the result of these three global indicators.
17	Use additional national and sub-national indicators to aid interpretation and to fill gaps for ecosystem services not covered by the three global indicators
18	Apply local knowledge and data to validate and interpret monitoring data.
19	Apply a continuous learning approach: anticipate, plan, track, interpret, review, adjust, create the next plan

implementation and monitoring strategies, and interpreting results of monitoring, which are applied in subsequent components of the framework. Countries pursuing LDN are encouraged to customize the causal framework for their own system(s).

Solid arrows indicate cause-effect relationships; dotted arrows indicate response relationships. Adapted from the Driving Force-Pressure-State-Impact-Response (DPSIR) framework (Smeets and Weterings, 1999), and the Driving force-Pressure-State-human/environment Impact-Response framework (DPSheIR) adopted by the UNCCD-AGTE (2013).

3.1.3. Interlinkages between land-based natural capital and ecosystem services

LDN seeks to maintain or enhance the land-based natural capital, which comprises the edaphic, geomorphological, hydrological and biotic features of a site. Fig. 3 illustrates the complex interrelationships between the features of land-based natural capital and the factors that influence them, emphasising the multiple linkages and processes. It also highlights ecosystem services delivered by land-based natural capital, how they meet human needs, and how they are influenced by land degradation processes, which are listed along with their drivers and pressures (natural and anthropogenic). This system model provides the

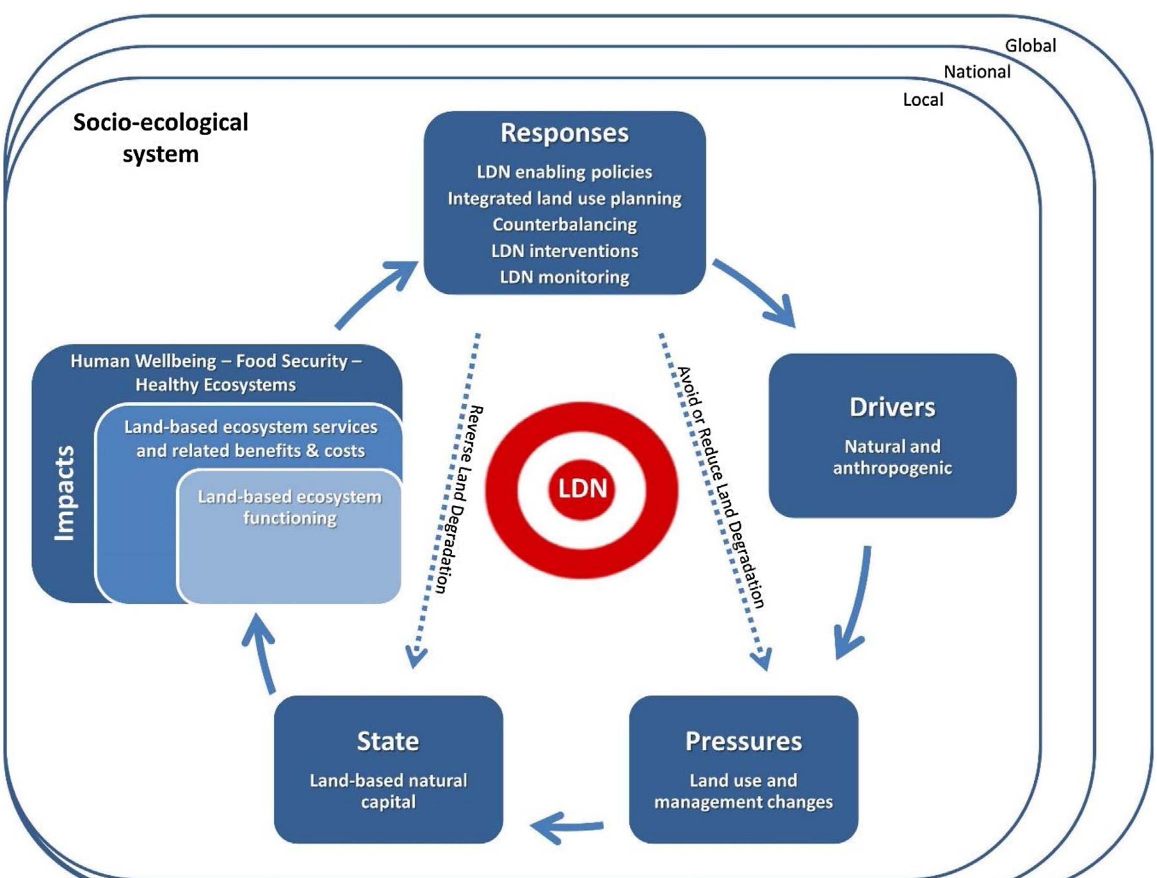

Fig. 2. Conceptualizing LDN in a cause and effect model within the socio-ecological system.

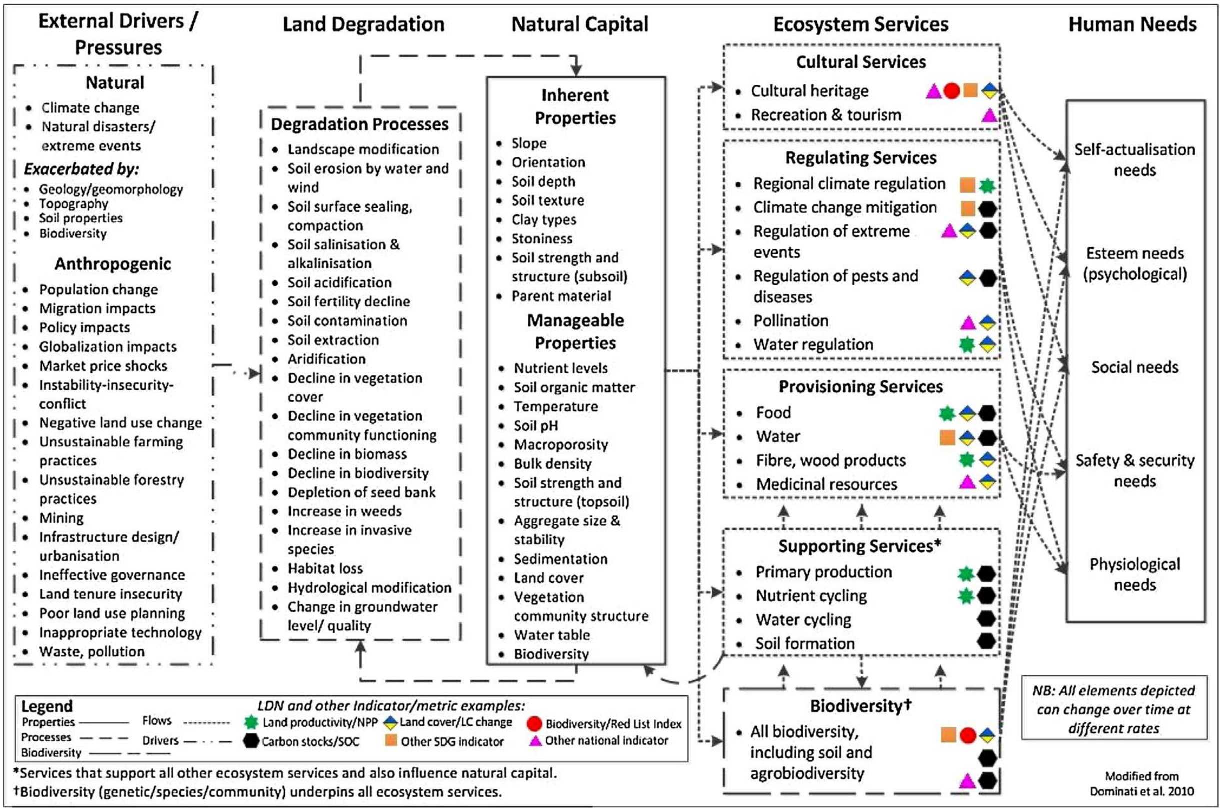

Fig. 3. System description relating the provision of ecosystem services to the land-based natural capital (with indicator/metric examples mapped to specific ecosystem services). Modified from Dominati et al. (2010).

basis for selection of indicators for monitoring LDN.

3.2. Module B: Frame of reference

Neutrality is the goal of LDN. To assess whether neutrality has been met, a reference, or baseline against which neutrality can be assessed needs to be established. Neutrality requires that there is no net loss of land-based natural capital between time zero (that is, the year 2015, when the UNCCD adopted LDN and SDGs were agreed) and the target date (2030, the target date for the SDGs).

The LDN baseline is therefore the initial value of each of the indicators used to monitor LDN. The baseline values of the indicators at the start of the implementation of the policy (t0) are compared to the values measured at the target date (t1) to determine the change in land-based natural capital. As the goal of LDN is no net loss, the LDN target is equal to the baseline, i.e. t1 = t0 (SI, Fig. S1). While neutrality is the *minimum* objective; countries may elect to set a more ambitious target, that is, to improve the land-based natural capital above the baseline, to increase the amount of healthy and productive land. Under rare circumstances, a country may elect an LDN target that includes some net loss, if they anticipate future land degradation that is not possible to counterbalance. In such circumstances, a country would need to justify this target.

To minimise the effects of seasonality and inter-annual climate variability on the selected indicators, the baseline value should be averaged across an extended period prior to t0 (Anyamba and Tucker, 2005). Ideally all countries would agree to use the same baseline period for tracking progress, to enhance comparability and assessment at the global scale.

3.3. Module C: Mechanism for neutrality

The neutrality mechanism supports the achievement of LDN through a pro-active focus on planning; it comprises the counterbalancing of *anticipated losses* in land-based natural capital with *planned gains*, within unique land types. The neutrality mechanism should be implemented at the resolution of the biophysical (e.g. catchment) or administrative (e.g. province) spatial domain of land use planning and decision making, and be scalable so that the results can be reported nationally. Ideally, neutrality would be integrated into existing land use planning processes, and implemented by existing institutions.

In each biophysical or administrative land unit, counterbalancing should be managed within the same land type ("like for like") to ensure conservation of unique ecosystems and to reduce risk of loss in ecosystem services. Land type is determined by *land potential*, which depends on inherent features aligned with key ecosystem functions and determines the inherent, long-term capacity of the land to sustainably generate ecosystem services (UNEP, 2016). A gain in one land type cannot counterbalance a loss in another land type. Further, the natural capital value of the counterbalancing site should be as high or greater than the site of loss, noting that land with the same biophysical characteristics may have different values for human wellbeing and livelihoods depending on where it is located. Counterbalancing losses in land types managed for conservation with gains in land types managed for production is not permitted.

Integrating counterbalancing with land use planning helps to identify the likely cumulative impacts of planning decisions, so that losses due to anticipated land degradation can be counterbalanced by equivalent gains. As *monitoring* for LDN is based on quantifying the area, per land type, of significant changes (positive and negative) in the indicators serving as proxies for capacity to deliver ecosystem services, counterbalancing aims to balance anticipated negative changes in the LDN indicators with actions planned to deliver positive changes at the target date. The counterbalancing concept (see Fig. S2, SI) is demonstrated in Table S5 (SI) for a hypothetical example showing a balance sheet of anticipated gains and losses generated at the planning stage.

LDN considers all forms of land degradation, whether due to human or natural causes, including the effects of active (e.g. granting permits for mining, land clearing; rezoning for urban development; restoration and rehabilitation projects; SLM initiatives) and passive land use decisions (e.g. continuation of agricultural practices known to deplete soil carbon) as well as the effects of natural drivers (e.g. drought, wildfire). While not a direct consequence of land use decisions, and difficult to predict, natural drivers will affect land-based natural capital and indicators for LDN, and their impacts may be modified by land use decisions, so their anticipated effects need to be counterbalanced to achieve LDN.

In planning counterbalancing interventions, it is important to consider resilience to, for example, the potential impacts of climate change, and the likely trade-offs between ecosystem services. Climate change may increase the risk of land degradation, leading to net losses despite efforts to reduce or reverse land degradation, making LDN more difficult to achieve. A land unit close to a spatial boundary of a land type may be at risk of changing state (and thus becoming a different land type) as a result of climate change, and thus would be less suitable for counterbalancing than another area of that land type that has greater resilience. A monoculture of a fast-growing exotic tree species may increase carbon stocks and provide wood products, but be vulnerable to pests and deliver low biodiversity co-benefits. Similarly, conversion to intensive agricultural production dependent on inputs of fertiliser and irrigation water may enhance land productivity and stimulate crop yields but increase risk of soil salinity and acidification, potentially reducing future productivity at the site, and lead to eutrophication of water bodies, with negative off-site consequences for human and natural systems.

The neutrality mechanism considers, for each land unit, the direction of potential change anticipated at that site. This binary approach, distinguishing land use decisions as having either anticipated positive or negative effects on land-based natural capital, carries an inherent risk: an area of relatively small gains could counterbalance an equal area where much larger losses are likely. Theoretically, the neutrality mechanism could consider not just the *direction* of change but also the *magnitude* of change. The basis for proposing the area-based approach is discussed further in Orr et al. (2017). The efficacy of the area-based approach should be evaluated during implementation of LDN. The costs, benefits, advantages and disadvantages of a magnitude-based approach should be evaluated to inform future decisions on adopting that approach.

3.4. Module D:- Achieving neutrality

Achieving LDN requires coordination of actions to 1) prevent degradation of healthy land, 2) reduce the level of land degradation, and 3) restore or rehabilitate degraded land, such that the areas of losses and gains are in balance, for each land type. This requires a process to *anticipate cumulative losses* and plan for gains in an optimal manner for each land type. The implementation of LDN may involve changes in land management practices by land users, and possibly transformation to different land uses. It will require decision-makers to actively engage with stakeholders to support these land management and land use decisions, recognizing that effective governance regimes can maximize the potential for success while protecting the rights of vulnerable individuals and communities. Multi-stakeholder platforms should leverage existing initiatives associated with local organizations such as civil society organizations and associations of small and medium-sized enterprises. While the focus of land use planning is local, decision-makers should be cognisant of national and international policies and initiatives that influence land use and distribution of benefits, such as trade agreements and sustainability schemes.

3.4.1. The LDN response hierarchy

The *LDN response hierarchy* of Avoid > Reduce > Reverse land degradation (Fig. 4) is based on the recognition that "prevention is better than cure" i.e. avoiding or reducing further land degradation is usually more cost-effective than efforts to reverse past degradation.

Avoiding and reducing land degradation on managed land requires the adoption of sustainable land management practices that seek to maintain land-based natural capital, for sustained delivery of ecosystem services. Reversing land degradation requires interventions that improve land-based natural capital, through restoration or rehabilitation.

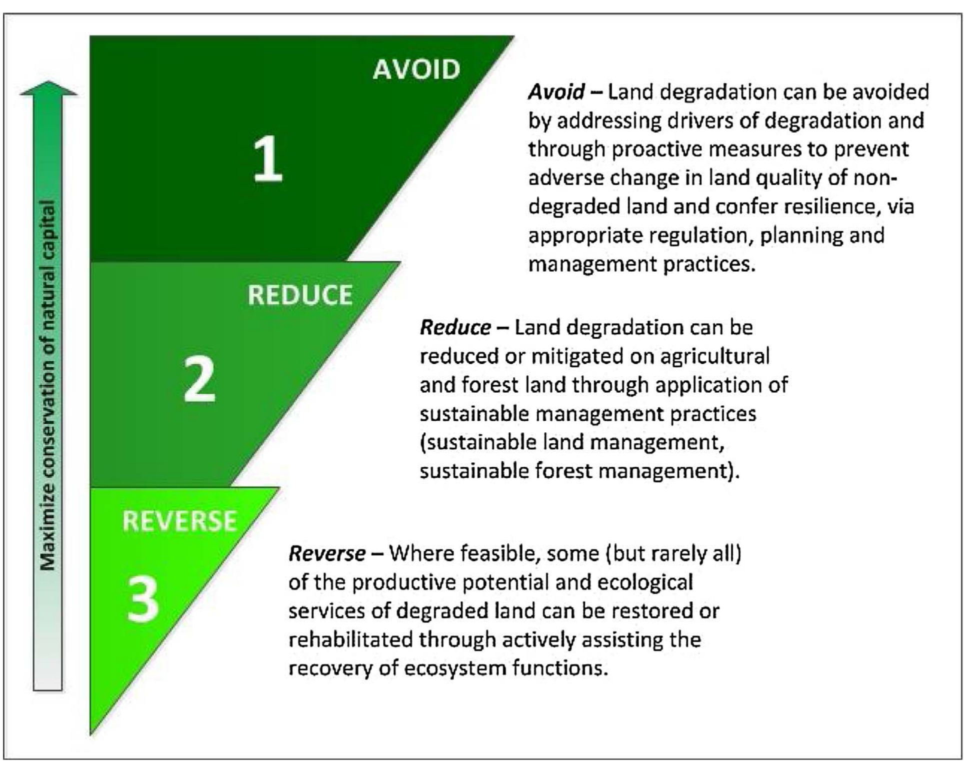

Fig. 4. The LDN response hierarchy encourages broad adoption of measures to avoid and reduce land degradation, combined with localised action to reverse degradation, to achieve LDN across each land type.

Restoration seeks to re-establish the pre-existing biotic integrity, in terms of species composition and community structure, while rehabilitation aims to reinstate ecosystem functionality with a focus on provision of goods and services rather than restoration (McDonald et al., 2016). The preferable option in each circumstance depends on the land potential, its land use history, its baseline condition, its potential uses and associated values, and likely impacts of climate change and other shocks and stressors. An ecosystem that undergoes restoration or rehabilitation can follow different trajectories (see SI Fig. S3), but is not likely to reach 100% of lost productivity and other ecosystem services, at least in the short to medium term (Benayas et al., 2009; Maron et al., 2012) Therefore, the most effective approach for maintaining land-based natural capital is to prevent land degradation where non-degraded land is at risk, followed by efforts to reduce or mitigate land degradation. However, of the three responses, only actions that *reverse* land degradation can *counterbalance losses* of land-based natural capital.

Pursuit of LDN will involve a combination of protection measures and wide-scale implementation of SLM, with localized restoration and/or rehabilitation actions undertaken strategically to deliver neutrality. Informed by the assessment of land potential, application of the response hierarchy will prioritise intervention on lands where avoidance of land degradation is achievable, followed by land where mitigation through adoption of SLM practices is suited, and lastly on land suitable for restoration or rehabilitation. The focus of the response hierarchy is therefore not on prioritizing investment for a given site, but rather on land use planning at landscape scale, pursuing the most appropriate combination of interventions to achieve LDN.

3.4.2. The logic model

Fig. 5 presents the logic model or impact pathway for achieving LDN, connecting inputs, activities, outputs and implementation interventions to the desired outcome (LDN), that is, the theory of change. This logic model should be adapted by users to suit their context and priorities, to identify critical actions, such as policy reforms to support effective implementation of LDN. To devise effective interventions and required enabling mechanisms, users may work backwards from the desired outcome (right-hand side of Fig. 5) to identify the key barriers and required actions. Thus, a critical first step is defining the goals with respect to country-specific circumstances. In this regard, the LDN Target Setting Programme assists countries to apply a participatory, transparent process to devise their goals and set the stage for implementing LDN (UNCCD-GM, 2016).

The key elements of the LDN logic model correspond to the columns in Fig. 5. Table S6 (SI) lists the elements of preparation and implementation of LDN showing requirements and outputs of each element.

3.4.3. Preliminary assessments

Preliminary assessment of enabling environment, land potential, land degradation status, resilience and socio-economic aspects support planning and implementation of LDN.

1. Enabling environment: evaluate, and where necessary, strengthen policies that facilitate LDN by encouraging SLM practices and activities designed to reverse land degradation across applicable sectors (e.g., environment, agriculture, water resources, urban), and that remove disincentives to adoption of these practices; ensure governance safeguards land tenure security, and encourages stakeholder participation in land use decisions; establish multi-stakeholder platforms and frameworks at local, national and regional levels to collaborate in planning, implementing and monitoring LDN. LDN planning and implementation should be embedded into existing planning processes and linked with policy initiatives for

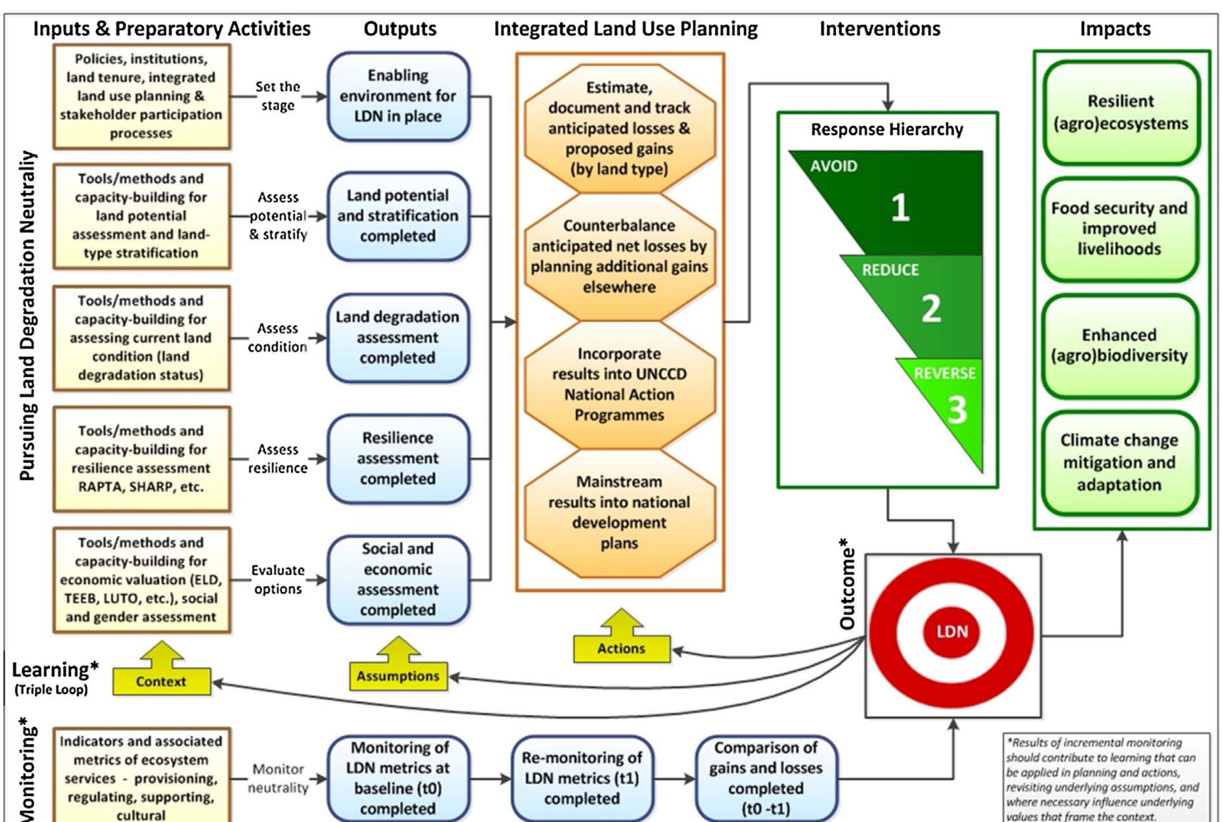

Fig. 5. Logic model for the effective implementation of LDN. Feedback arrows indicate the importance of "triple loop learning" (Section 3.4.3), through which information from monitoring is used to test hypotheses and modify action plans and the conceptual system model.

climate change, biodiversity and sustainable development. Application of guidelines for the responsible governance of tenure (FAO, 2012), including transparent and participatory land use planning, is recommended to protect the land use rights of local land users.

(i) Land potential: land potential, the inherent, long-term capacity of the land to sustainably generate ecosystem services (UNEP, 2016), is the basis for classifying land types. Land potential is determined by inherent features aligned with key ecosystem functions such as geomorphology, topography, climate, vegetation structure and species assemblages, and relatively static soil properties, such as texture. Land potential influences vegetation community composition and risk of land degradation, and determines suitability for uses such as cropping, grazing, forestry, infrastructure or urban development. Stratification into land units should apply land type as the primary stratum, and current vegetative cover (which reflects responsive soil properties, such as organic matter level, that influence land condition), as a secondary division.

(ii) Initial land degradation status: current land condition is used in prioritising interventions to reduce and reverse degradation, and may be determined from the same indicators used for determining the baseline: a declining trend in NPP that is inconsistent with the rainfall trend suggests that degradation is occurring (Section 3.8); NPP that is consistently below historical values for that location or typical values for that land type suggests that the site is degraded.

(iii) Resilience of current and proposed land uses and management: Resilience refers to the ability of a system to continue to deliver the same ecosystem services despite disturbance. Resilience assessment considers the current condition of the land, the adaptive capacity of the land use system, the system's vulnerability to known shocks and trends, general resilience to cope with unknown shocks, and proximity to known thresholds (O'Connell et al., 2015). Resilience assessment may identify the need for adaptation to manage risks, or transformation in some parts of the system to cope, for example, with the anticipated interactions between climate change and land degradation risks. Tools include the Resilience, Adaptation Pathways and Transformation Assessment (RAPTA, O'Connell et al., 2016) framework and the Self-evaluation and Holistic Assessment of climate Resilience of farmers and Pastoralists (SHARP, FAO).

(iv) Socio-economic assessment: Because the economic benefits of achieving LDN are both public and private, and accrue over the long term, and there are often trade-offs, the full suite of benefits and costs should be considered in planning LDN. Tools include the United Nations Statistics Division (UNSD) System of Environmental-Economic Accounting (SEEA) Experimental Ecosystem Accounts, The Economics of Ecosystems and Biodiversity (TEEB), or modelling and assessment approaches such as the Land Use Trade-Offs (LUTO) model (Bryan et al., 2015).

This set of preliminary assessments provides the basis for selecting sites for LDN interventions designed to avoid, reduce or reverse degradation. Particularly in the case of restoration and rehabilitation actions taken to reverse degradation, it is important to ensure that the most suitable sites are selected, in terms of economic and environmental costs and benefits, and resilience of the planned interventions. See also Sections 3.3 and 3.4.1.

A further preparatory step involves establishment of mechanisms for learning and adaptive management. Ideally both individual and social learning (Reed et al., 2010) are integrated into an overall approach to implementing LDN that encourages "triple-loop learning", where the first learning loop can lead to incremental changes in routine actions, the second leads to revisiting underlying assumptions, and the third may influence underlying values and core beliefs (Stafford Smith et al., 2009). Information from interim monitoring should lead to refinements in integrated land use planning decisions and associated LDN interventions (first learning loop), revisiting underlying assumptions drawn from the preliminary assessments (second loop), and, where necessary, influence underlying values that frame the context and enable an environment conducive to achieving LDN (third loop) (see Fig. 5).

3.5. Module E: Monitoring LDN

3.5.1. Indicators and metrics for LDN

The LDN conceptual framework specifies a minimum set of indicators to reflect the key processes that underpin land-based natural capital. Selecting globally relevant indicators for land degradation has inherent challenges due to the wide variability in land degradation processes as well as practical considerations concerning capacity of countries to collect, analyse, interpret and report progress toward achieving LDN.

While indicators describe *what* to measure, metrics describe *how* the indicators are assessed. Fig. S4 (SI) provides examples relating ecosystem services to indicators, metrics and data sets. Monitoring LDN requires metrics that are universally applicable and interpretable, and, preferably, quantifiable with available data sets. Fig. 3 shows the outcome of the expert workshop process to map indicators/metrics (coloured symbols) to specific land-based ecosystem services. This process determined that three indicators already used for UNCCD reporting (UNCCD-AGTE, 2013) and proposed for the SDGs, are a reasonable proxy for change in the land-based natural capital: land cover (metric: physical land cover), land productivity (metric: net primary productivity, NPP) and carbon stocks (metric: soil organic carbon, SOC). Furthermore, these indicators are complementary, reflecting different features of the system: land cover is a highly responsive measure, reflecting land use dynamics, that reveals change in vegetative cover such as through land conversion and resulting habitat fragmentation; land productivity captures relatively fast changes in ecosystem function; while soil organic carbon reflects slower changes resulting from the net effects of biomass growth and disturbance/removal, and is an indicator of resilience.

These indicators should be supplemented by national (or sub-national) level indicators to cover the land-based ecosystem services that are important in each context. Indicators of social and economic impact of LDN should also be included. The optional narrative indicators for reporting under the UNCCD (UNCCD, 2013) and indicators for relevant SDGs could provide data for monitoring broader impacts of LDN interventions.

Progress towards LDN should also be monitored through process indicators that record actions taken along the LDN implementation pathway. Relevant indicators could include, for example, measures of progress in establishing enabling policies and monitoring systems, and interventions such as area of SLM adoption and area of restoration or rehabilitation activities; proportion of catchments with LDN plans.

Monitoring LDN involves assessing change in the metrics compared with the baseline (t0) values. The framework does not prescribe datasets for the three global indicators. Data for monitoring LDN could be collected by international organizations, national land management bodies, space agencies and research institutions working together to facilitate access to remotely sensed and ground-based measurements including citizen science data (e.g. LandPKS initiative, Herrick et al., 2016).

Monitoring provides opportunities for capacity building and learning; data for testing hypotheses that underpin this framework, the counterbalancing decisions and the interventions implemented; and knowledge to inform adaptive management.

3.5.2. Using the indicators to evaluate LDN status

There is no scientific basis for combining the three indicators into a composite indicator to generate an aggregated value. Aggregation would mask changes in the individual measures. Gains in one measure cannot compensate for losses in another because all are complementary, not additive, components of land-based natural capital. Therefore, the "one-out, all-out" rule is applied; if one of the indicators/metrics shows a negative change, LDN is not achieved, even if the others are substantially positive. This is the most conservative way to integrate the separate indicator values, consistent with the precautionary principle, however it is prone to false positive error (Borja et al., 2014).

Monitoring LDN therefore assesses losses as the area, per land type, in which at least one of the three indicators shows a negative change, and gains as the area, per land type, over which there is a positive change in at least one of the indicators (and none shows a negative change). Neutrality is achieved when the area of losses equals the area of gains, within each land type, and across land types, at national scale.

Some transitions may be universally agreed as negative land cover change, such as deforestation of high conservation value forest; or conversion of natural areas and productive farmland to settlements. Countries may declare other specific transitions to be negative (e.g. bush encroachment), even though the metrics SOC and NPP may show positive change.

Each land unit (a polygon, based on aggregation of measurements inside that unit, either pixels or points) is "scored" as loss/stable/gain, as illustrated in Fig. S5 (SI). The areas of gains and losses are tabulated for each land type in each biophysical or administrative domain. These are then summed to determine the LDN status for each land type in a country, and combined across land types to determine the LDN status for the entire country.

A country can select supplementary indicators for locally-relevant ecosystem services that are not covered by the three global indicators. The country may choose to apply one or more of these using the one-out, all-out approach, in addition to the three global indicators. It should be noted that the one-out, all-out approach will become increasingly conservative as the number of indicators applied in this manner increases. Alternatively, supplementary indicators may be used only to enhance understanding of land condition, and to interpret the results of the three global indicators, to inform responses.

3.6. Verification and interpretation

Outputs of LDN monitoring need to be verified against national and local data sets and expert opinion, with input from local stakeholders. Verification is required to ensure that assessment of LDN status accurately reflects changes on the ground, including changes in aspects of land-based natural capital not detected by the three global indicators.

Verification by stakeholders is also required to identify "false positives", where significant positive change in one or more indicators may result from an undesirable trend, such as shrub encroachment on grassland which results in a higher NPP and perhaps SOC, though it represents a loss of ecosystem services, with less forage available for grazing animals and wildlife. A "false negative" result could also be obtained for example where a water reallocation decision leads to conversion from irrigated agriculture to dryland pastoralism, with significantly lower NPP but lower risk of land degradation through salinization. In cases where a false positive or a false negative have been identified, countries could report such anomalies, backed by evidence, to provide an adjusted assessment of LDN status.

Verification should contribute to the learning process and adaptive management. Local communities could participate in verification, applying methods such as the Land Degradation Surveillance Framework (Vågen et al., 2015) or LandPKS (Herrick et al., 2016).

3.7. The area-based approach to monitoring neutrality

LDN status is evaluated from the *area of land* that experiences significant change in the indicators (either positive or negative), and does not consider the *magnitude of change* in the indicators. This creates the risk that severe degradation will be considered to be counteracted by a small improvement on an equal area, such as has occurred in biodiversity offsetting frameworks (Gordon et al., 2015; McKenney and Kiesecker, 2010; Maron et al., 2016). This could result in substantial under-estimation of land degradation (see example in SI Table S7). This table demonstrates that a magnitude-based approach could be applied using the same metrics adopted for the area-based approach. The pros and cons of the magnitude-based approach relative to the area-based approach are discussed in Orr et al. (2017). Although the magnitude-based approach has disadvantages, it addresses an important concern, that is, that the area-based approach may not adequately reflect changes in land-based natural capital resulting from land degradation and measures to reverse it. Therefore, it is suggested that the magnitude of change in each of the indicators could be calculated as supplementary information, using the approach shown in Table S7 (SI). Any discrepancy between the results of the area-based and magnitude-based approaches should trigger an investigation to identify causes and appropriate response.

3.8. Additional considerations to aid interpretation and guide adaptive management

The goal of LDN is to inform and enhance land management, to minimise degradation and encourage actions to reverse degradation, to sustain and enhance land-based ecosystem services. Thus, adaptive learning based on results of monitoring and subsequent verification processes should be used to inform evaluation of the effectiveness of past interventions in maintaining ecosystem services, and to plan future land management.

Interim monitoring, that occurs between t0 and t1 (e.g. regular reporting to the UNCCD), provides the opportunity to evaluate progress, adjust the theory of change, and modify implementation plans to enhance the prospects of meeting the LDN target.

External shocks and trends, such as climate change, can result in a shift from one land type to another, characterised by different species composition and/or level of productivity (O'Connell et al., 2015). For example, a land unit affected by overgrazing in combination with drought may lose ground cover and cross a threshold to a low productivity state. Unpalatable invasive grasses may diminish the capacity to continue grazing or to restore original native vegetation. A change in state in one land unit detected through interim monitoring could suggest a need for refocusing LDN interventions on another land unit with greater likelihood of improvement.

Comparison between observed and expected change in the value of LDN metrics based on climatic patterns allows the impact of land use and management to be distinguished from natural factors such as rainfall variability (Bastin et al., 2012). Decline in NPP that is inconsistent with rainfall pattern, reflecting a reduction in water use efficiency, is a strong indication of degradation. Conversely, an increase in NPP suggests success in restoration or rehabilitation. Thus, comparison with rainfall patterns assists in interpreting monitoring results, with respect to land degradation status and risk, and required management responses.

Lastly, the three global indicators of LDN can be used for monitoring trends in land condition. Trends in each of the indicators over a 10–15 year period can reveal areas with declining condition, which can inform planning of interventions.

4. Conclusion and recommendations

The scientific conceptual framework for LDN provides a foundation to support pursuit of LDN. It focuses on the goal of LDN and the supporting processes required to deliver this goal, including biophysical and socio-economic aspects, and their interactions. Achievement of

LDN requires effort to avoid net loss of land-based natural capital relative to the baseline. The framework introduces the neutrality mechanism, which involves projecting the likely cumulative impacts of land use and land management decisions, at landscape scale, then counterbalancing anticipated losses with measures to achieve equivalent gains, within individual land types. Actions to achieve LDN include sustainable land management practices that avoid or reduce degradation, coupled with efforts to reverse degradation through restoration or rehabilitation of degraded land. The response hierarchy of *Avoid > Reduce > Reverse land degradation* articulates the priorities in planning LDN interventions.

Land productivity (NPP), carbon stocks (SOC) and land cover, which reflect land based natural capital, are selected as global indicators for monitoring LDN status. In addition, it is recommended that guidelines be developed to assist countries in determining what land cover transitions should be counted as negative land cover change.

Due to the fundamental relationships between land-based natural capital and ecosystem services including climate change mitigation and biodiversity conservation, the land-based indicators identified for LDN monitoring are also relevant to the climate change and biodiversity conventions. The potential for synergies through coordinated monitoring and reporting to the three Rio conventions has been previously identified (e.g. Cowie et al., 2007); LDN could be the catalyst that allows this potential to be realised. Opportunities for synergies include integration of planning for interventions, to minimise trade-offs, and linking monitoring and reporting of biophysical land-based indicators to reduce costs, enhance collaboration and facilitate interpretation. Integrated land use planning for LDN could become the instrument for landscape management to deliver multiple environmental and socio-economic objectives, including pursuit of the Sustainable Development Goals.

Disclaimer

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envsci.2017.10.011.

References

Anyamba, A., Tucker, C.J., 2005. Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003. J. Arid Environ. 63, 596–614.

Bastin, G., Scarth, P., Chewings, V., Sparrow, A., Denham, R., Schmidt, M., O'Reagain, P., Shepherd, R., Abbott, B., 2012. Separating grazing and rainfall effects at regional scale using remote sensing imagery: a dynamic reference-cover method. Remote Sens. Environ. 121, 443–457.

Benayas, J.M.R., Newton, A.C., Diaz, A., Bullock, J.M., 2009. Enhancement of biodiversity and ecosystem services by ecological restoration: a meta-analysis. Science 325, 1121–1124.

Borja, A., Prins, T.C., Simboura, N., Andersen, J.H., Berg, T., Marques, J.-C., Neto, J.M., Papadopoulou, N., Reker, J., Teixeira, H., 2014. Tales from a thousand and one ways to integrate marine ecosystem components when assessing the environmental status. Front. Mar. Sci. 1, 72.

Bryan, B.A., Crossman, N.D., Nolan, M., Li, J., Navarro, J., Connor, J.D., 2015. Land use efficiency: anticipating future demand for land-sector greenhouse gas emissions abatement and managing trade-offs with agriculture, water, and biodiversity. Glob. Change Biol. 21, 4098–4114.

Cowie, A., Schneider, U.A., Montanarella, L., 2007. Potential synergies between existing multilateral environmental agreements in the implementation of land use, land-use change and forestry activities. Environ. Sci. Policy 10, 335–352.

Dominati, E., Patterson, M., Mackay, A., 2010. A framework for classifying and quantifying the natural capital and ecosystem services of soils. Ecol. Econ. 69, 1858–1868.

FAO, 2012. Voluntary Guidelines on the Responsible Governance of Tenure of Land, Fisheries and Forests in the Context of National Food Security. FAO, Rome.

FAO, 2017. Self-evaluation and Holistic Assessment of climate Resilience of farmers and Pastoralists (SHARP). FAO, Rome. http://www.fao.org/in-action/sharp/en/.

Gordon, A., Bull, J.W., Wilcox, C., Maron, M., 2015. FORUM: perverse incentives risk undermining biodiversity offset policies. J. Appl. Ecol. 52, 532–537.

Herrick, J.E., Beh, A., Barrios, E., Bouvier, I., Coetzee, M., Dent, D., Elias, E., Hengl, T., Karl, J.W., Liniger, H., 2016. The land-potential knowledge system (LandPKS): mobile apps and collaboration for optimizing climate change investments. Ecosyst. Health Sustain. 2.

Millennium Ecosystem Assessment (MA), 2005. Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC.

Maron, M., Hobbs, R.J., Moilanen, A., Matthews, J.W., Christie, K., Gardner, T.A., Keith, D.A., Lindenmayer, D.B., McAlpine, C.A., 2012. Faustian bargains? Restoration realities in the context of biodiversity offset policies. Biol. Conserv. 155, 141–148.

Maron, M., Ives, C.D., Kujala, H., Bull, J.W., Maseyk, F.J., Bekessy, S., Gordon, A., Watson, J.E., Lentini, P.E., Gibbons, P., 2016. Taming a wicked problem: resolving controversies in biodiversity offsetting. Bioscience biw038.

McDonald, T., Gann, G.D., Jonson, J., Dixon, K.W., 2016. International Standards for the Practice of Ecological Restoration—Including Principles and Key Concepts, first edition. Society for Ecological Restoration (SER), Washington, D.C.

McKenney, B.A., Kiesecker, J.M., 2010. Policy development for biodiversity offsets: a review of offset frameworks. Environ. Manage. 45, 165–176.

Montanarella, L., Pennock, D.J., McKenzie, N., Badraoui, M., Chude, V., Baptista, I., Mamo, T., Yemefack, M., Singh Aulakh, M., Yagi, K., 2016. World's soils are under threat. Soil 2, 79–82.

O'Connell, D., Walker, B., Abel, N., Grigg, N., 2015. The Resilience, Adaptation and Transformation Assessment Framework: From Theory to Application. CSIRO, Dickson, ACT, Australia.

O'Connell, D., Abel, N., Grigg, N., Maru, Y., Butler, J., Cowie, A., Stone-Jovicich, S., Walker, B., Wise, R., Ruhweza, A., 2016. Designing Projects in a Rapidly Changing World: Guidelines for Embedding Resilience, Adaptation and Transformation into Sustainable Development Projects (Version 1.0). Scientific and Technical Advisory Panel (STAP) of the Global Environment Facility (GEF), Washington, D.C. http://www.stapgef.org/the-resilience-adaptation-and-transformation-assessment-framework.

Orr, B.J., Cowie, A.L., Castillo Sanchez, V.M., Chasek, P., Crossman, N.D., Erlewein, A., Louwagie, G., Maron, M., Metternicht, G.I., Minelli, S., Tengberg, A.E., Walter, S., Welton, S., 2017. Scientific Conceptual Framework for Land Degradation Neutrality. A Report of the Science-Policy Interface. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany ISBN 978-92-95110-42-7 (hard copy), 978-92-95110-41-0 (electronic copy).

Reed, M., Evely, A.C., Cundill, G., Fazey, I.R.A., Glass, J., Laing, A., Newig, J., Parrish, B., Prell, C., Raymond, C., 2010. What is social learning? Ecol. Soc. 15.

Safriel, U., 2017. Land Degradation Neutrality (LDN) in drylands and beyond-where has it come from and where does it go. Silva Fenn. 51.

Smeets, E., Weterings, R., 1999. Environmental Indicators: Typology and Overview. European Environment Agency, Copenhagen.

Stafford Smith, D.M., Abel, N., Walker, B., Chapin III, F.S., 2009. Drylands: coping with uncertainty, thresholds, and changes in state. Principles of Ecosystem Stewardship. Springer pp. 171–195.

UN-Habitat-GLTN, 2016. Scoping and Status Study on Land and Conflict: Towards UN System-Wide Engagement at Scale. United Nations Human Settlements Programme Report 5/2016. Available at: http://www.gltn.net/index.php/publications/publications/download/2-gltn-documents/2343-scoping-and-status-study-on-land-and-conflict.

UNCCD, 2013. Report of the Conference of the Parties on its eleventh session, held in Windhoek from 16 to 27 September 2013. Part two: Action taken by the Conference of the Parties at its eleventh session. ICCD/COP(11)/23/Add.1. United Nations Convention to Combat Desertification (UNCCD), Bonn.

UNCCD, 2016. Report of the Conference of the Parties on its twelfth session, held in Ankara from 12 to 23 October 2015. Part two: Actions. ICCD/COP(12)/20/Add.1. United Nations Convention to Combat Desertification (UNCCD), Bonn. http://www.unccd.int/Lists/OfficialDocuments/cop12/20add1eng.pdf.

UNCCD-AGTE, 2013. Refinement of the set of impact indicators on strategic objectives 1, 2 and 3. Recommendations of the ad hoc advisory group of technical experts ICCD/COP(11)/CST/2 and Corr.1. 10 July 2013. United Nations Convention to Combat Desertification (UNCCD).

UNCCD-GM, 2016. Achieving Land Degradation Neutrality at the country level ? Building blocks for LDN Target SettingThis should say Achieving Land Degradation Neutrality at the country level: Building blocks for LDN target setting. ie delete the "?". Global Mechanism (GM) of the United Nations Conventions to Combat Desertification (UNCCD), Bonn, Germany Available online: http://www2.unccd.int/sites/default/files/documents/160915_ldn_rgb_small%20%281%29.pdf.

UNEP, 2016. In: Herrick, J.E., Arnalds, O., Bestelmeyer, B., Bringezu, S., Han, G., Johnson, M.V., Kimiti, D., Lu, Yihe, Montanarella, L., Pengue, W., Toth, G., Tukahirwa, J., Velayutham, M., Zhang, G. (Eds.), Unlocking the Sustainable Potential of Land Resources: Evaluation Systems, Strategies and Tools. A Report of the Working Group on Land and Soils of the International Resource Panel. United Nations Environment Programme (UN Environment), Nairobi Available at: http://resourcepanel.org/reports/unlocking-sustainable-potential-land-resources.

Vågen, T.-G., Winowiecki, L.A., Tamene Desta, L., Tondoh, J.E., 2015. The Land Degradation Surveillance Framework (LDSF) – Field Guide v4.1. World Agroforestry Centre, Nairobi, Kenya (14 pp.).

Weiss, C.H., 1995. Nothing as practical as good theory: Exploring theory-based evaluation for comprehensive community initiatives for children and families. New approaches to evaluating community initiatives: Concepts, methods, and contexts 1. pp. 65–92.