How Do We Know When We Achieve Land Degradation Neutrality in Forests? A Systematic Review

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Abstract

This systematic review develops a comprehensive understanding of how land degradation is measured with respect to forests, and what qualitative and quantitative methods are being utilised in the pursuit of land degradation neutrality (LDN) generally. Scopus and Environmental Abstracts (EVA) databases were searched for peer-reviewed studies from 1998–2021 using key search terms including 'land degradation neutrality', 'soil' and 'forest'.

Of the 53 included studies, most articles (n = 25) are experimental reports, and the next most common classification (n = 14) is literature reviews. Studies tended to be longitudinal (mean length of 15.4 years) and Eurasia-centric.

Almost all extant research focuses on the indicators rather than the drivers of land degradation. Choosing indicators to measure remains contentious; however, most research uses those prescribed by the United Nations Convention to Combat Desertification: land cover, net primary productivity and soil organic carbon. Despite this convergence around which indicators to monitor, there is no standardisation in the methods used to do so. Therefore, no meaningful comparison between countries or even studies can be made.

This lack of standardisation and bias towards indicators instead of drivers is important because, under the current paradigm, land managers seeking to prevent or offset forest degradation cannot do so with any certainty. Until these issues are addressed, it will be impossible to track progress towards the United Nations Sustainable Development Goal 15.3 for global LDN, and large-scale conservation work in this area is based on guesswork.

How will we know when we achieve LDN in forests, globally? Based on current research, we will not. Future research must seek standardised ways to quantify land degradation based on its drivers: erosion, urbanisation and human activity, drought and desertification, and pollution.

Keywords: Land degradation neutrality, land degradation neutrality in forests, quantitative methods for land degradation neutrality research, Sustainable Development Goal 15.3, sustainable forest management, need for standardisation in forest degradation research

Introduction

Land degradation overview

Land degradation is widely conceived of as a loss of primary productivity, soil carbon, or a change in land use/land cover (LULC), which negatively impacts the ability of ecosystems to provide important ecosystem services (ELD Initiative, 2015: 8–11; Orr *et al.*, 2017: 33–35). It is a positive feedback cycle, as land degradation contributes greatly to social and ecological losses that, in turn, directly accelerate the land degrading processes of soil erosion, salinisation, land pollution, biodiversity loss and reductions in soil organic carbon (Zhao *et al.*, 2021: 5411–12). For these reasons, halting and remediating degraded land has been high on the United Nations' agenda since the 1992 Rio de Janeiro Earth Summit (United Nations Sustainable Development, 1992). This laid the foundations for the three Rio Conventions of the United Nations: Convention on Biological Diversity, Convention to Combat Desertification and the United Nations Framework Convention on Climate Change. The processes that shape and drive land degradation are diverse and complex and predominantly driven by human pressures on land (Conacher, 2009).

Land degradation has been amplified since the twentieth century due to combined pressures of agricultural and livestock production (over-cultivation, overgrazing, forest conversion), urbanisation, deforestation, and extreme weather events such as droughts and coastal surges associated with climate change (IPCC, 2019: 7–19).In 2015, the extent of degraded land was estimated to lie between 1 billion and 6 billion hectares, covering 73 per cent of the world's dryland rangelands and 47 per cent of marginal rainfed croplands (Gibbs and Salmon, 2015: 14; Gisladottir and Stocking, 2005: 100). If the current land degradation rate of 12 million hectares annually continues, more than 90 per cent of the Earth's land will be degraded by 2050 (Jiang *et al.*, 2021: 1). In many cases, unsustainable human actions that cause land degradation can bring short-term socio-economic benefits at the local scale (Debonne *et al.*, 2021: 7); however, estimations of global economic losses from land degradation range from USD $231 billion to USD $20.2 trillion annually (Tsvetnov *et al.*, 2021: 441). This is a severe and complex global problem impacting the food security, socio-economic development, livelihoods, health and wellbeing of at least 1.5 billion people (Stavi and Lal, 2015: 44–45). Therefore, it is critical to implement methods that both halt the rate of land degradation and restore degraded lands.

Land degradation neutrality

Land degradation neutrality (LDN) is a concept created to address the worsening land degradation challenges globally. LDN has been coined and defined by the United Nations Convention to Combat Desertification (2015) as 'a state whereby the amount and quality of land resources, necessary to support ecosystem functions and services and enhance food security, remains stable or increases within specified temporal and spatial scales and ecosystems'. The concept is supplemented by an overarching response hierarchy prioritising avoidance, then reduction, then reversal of land degradation, which maximises the conservation of terrestrial natural capital (Crossland *et al.*, 2018: 51–52). Since being defined in 2015, the concept of LDN has increased steadily in prominence, as shown in Figure 1. The slight downturn in LDN literature publications in 2020 is an outlier to this trend – likely due to the COVID-19 pandemic, which was globally disruptive that year.

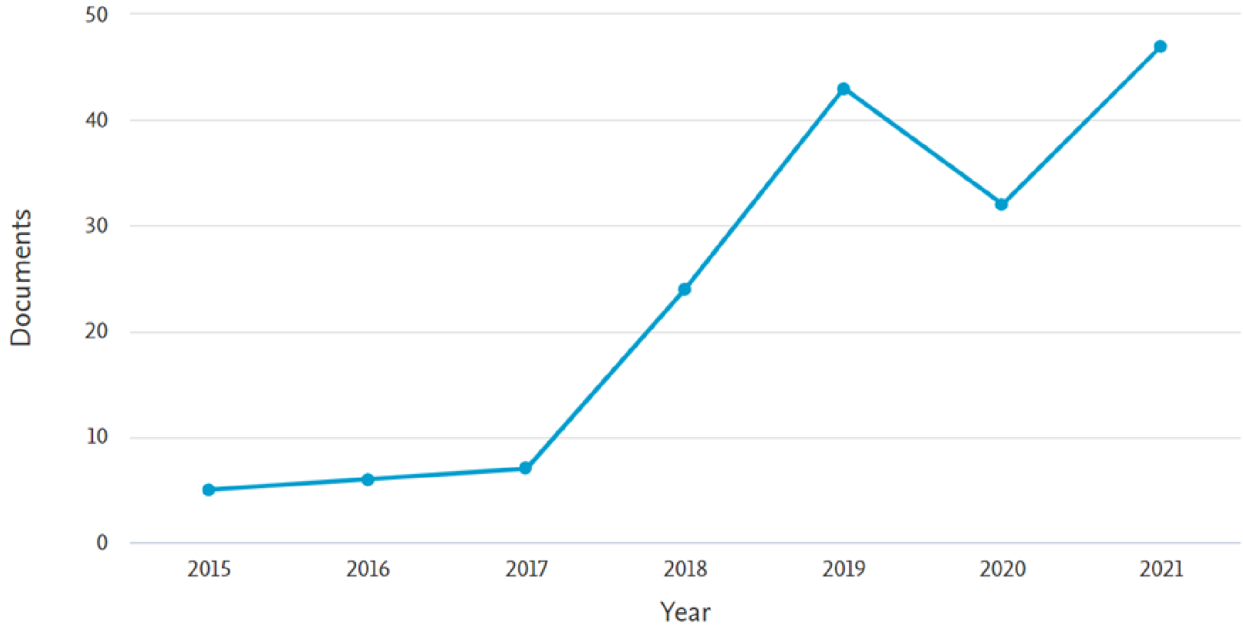

Figure 1: The number of articles published with the term 'land degradation neutrality' in the title, abstract or keywords in the Scopus database (Scopus, 2021).

LDN is the objective of United Nations Sustainable Development Goal (SDG) 15.3 (United Nations, 2020). It aims to prevent land degradation and remediate degraded land to a productive and stable state such that there is no net loss in the amount of natural capital between 2015 (when the Sustainable Development Goals were agreed) and the target year of 2030 (Cowie *et al.*, 2018: 29). The achievement of LDN also underpins the long-term achievement of several other SDGs, such as SDG 13 on climate action and SDG 1 on poverty alleviation through the intersections of food, water, migration, conflict, energy security, human health and biodiversity loss (Kapur *et al.*, 2006; Sietz *et al.*, 2017: 2308; Wunder and Bodle, 2019: 46).

Forest degradation and agricultural expansion

Forests harbour significant ecological assets that provide valuable ecosystem services, including carbon sequestration, high species richness, water, soil and air quality regulation, maintenance of the hydrological system, soil formation and spiritual/cultural connections (ELD Initiative, 2015: 8–11; Gibbs *et al.*, 2010: 16736). However, forests are often degraded for short-term economic benefit with little consideration for these complex and difficult-to-replace services. Forests globally are threatened by the anthropogenic pressures of logging, agricultural expansion, infrastructure construction, urbanisation and climate change (Kapur *et al.*, 2006: 293; Kissinger, 2012: 5–16; Ramankutty *et al.*, 2008: 1).

Despite reforestation and afforestation efforts being commonly employed by countries to restore degraded lands and address demand for fuel and construction timber (Kissinger, 2012: 17–20), it has been estimated that there is a net loss of 10 billion trees per year: 15 billion cut down, 5 billion new growths (Crowther *et al.*, 2015). Additionally, old-growth forests provide higher quality ecosystem services than new plantations, including greater water retention, carbon storage and soil stability (Lindenmayer and Laurance, 2017: 1438–42). Therefore, deforestation would continue to deplete Earth's natural capital, even if the net loss of trees was zero.

Today, around 45 per cent of temperate deciduous forests have been replaced by agricultural land, and around 27 per cent of tropical forests have been cleared (Ramankutty *et al.*, 2008: 14). This massive clearing was spearheaded by agricultural expansion in the 1980s and 1990s, during which time more than 80 per cent of new farmland in tropical areas replaced forests rather than repurposing already cleared land (Gibbs *et al.*, 2010: 16736). Clearing forests for agriculture not only affects forest ecosystems directly but also contributes to ~12 per cent of total anthropogenic CO_2 emissions, reduces soil fertility and reduces global biodiversity (Bastin *et al.*, 2019: 365; Friedlingstein *et al.*, 2010: 811). Hence, progress towards forest degradation neutrality (FDN) is a key element of LDN.

To achieve sustained progress towards FDN will require accurate and reliable long-term data on the impact of land management strategies on forests. Therefore, it is important to understand how forest degradation is being assessed globally, and to consider whether these assessments are fit for purpose.

The scope of this systematic review is to analyse peer-reviewed papers that focus on land degradation neutrality and forests globally. This systematic review aims to develop a comprehensive understanding of how the scientific community is measuring forest degradation, and what qualitative and quantitative methods are being utilised to assess progress towards FDN and LDN more generally.

Methods

This review was conducted in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher *et al.*, 2009). The electronic databases selected for this review were the Scopus and Environmental Abstracts (EVA) databases, chosen based on their extensive access to literature within the fields of science and environmental/land management. The search terms and search details used for each database, along with their associated filters and ranges, are presented in Table 1. Two searches returned a total of 143 articles from Scopus and a third search returned 90 articles from EVA, totalling 233 papers altogether. However, many papers unearthed by EVA were duplicated in the Scopus searches – which inflates the number of initial records, as seen in Figure 2.

During the initial gathering of articles, search terms remained relatively broad to ensure the inclusion of all publications relevant to LDN, even if they did not specifically address FDN. Key search terms included ‘land degradation neutrality’, ‘soil’ and ‘forest’. ‘Soil’ was considered a key search term, despite not always being directly affected by forest degradation processes, because it is impossible for a forest to thrive on poor substrate material, and soil organic carbon is stipulated by the United Nations Convention to Combat Desertification(2015) as a primary LDN indicator.

Papers were not excluded by publication date or geographic location as the concept of LDN is relatively new (Figure 1), and comparison between regions was desirable. Literature reviews, meta-analyses and systematic reviews were included, while grey literature, dissertations, reports and other non-peer-reviewed sources were excluded.

The process of identification and screening is illustrated through the adapted PRISMA flow diagram (Figure 2) (Moher *et al.*, 2009).

Date	Search terms	Database	Years covered	Number of results	Updated search?
08/09/2021	'Land Degradation Neutrality' AND soil AND forest AND (LIMIT-TO (SUBJAREA, 'ENVI') OR LIMIT-TO (SUBJAREA, 'AGRI')) AND (LIMIT-TO (PUBSTAGE, 'final')) AND (LIMIT-TO (DOCTYPE, 'ar') OR LIMIT-TO (DOCTYPE, 're')) AND (LIMIT-TO (SRCTYPE, 'j'))	Scopus	2015–2021	114	No
08/09/2021	((TITLE-ABS-KEY (degradation) AND TITLE-ABS-KEY (*forest*) AND TITLE-ABS-KEY (rehabilitation OR restoration OR remediation))) AND (soil) AND (TITLE-ABS-KEY ('ex situ' OR offsite OR external OR neutral OR neutrality)) AND (LIMIT-TO (SRCTYPE, 'j')) AND (LIMIT-TO (DOCTYPE, 'ar'))	Scopus	2015–2021	33	No
17/09/2021	clear* AND neutrality AND degradation AND (soil OR land) AND Forest With filters: Peer-reviewed journal articles; Articles; Environmental Sciences and Ecology; Environmental Sciences; Land Use; Agriculture	EVA: Environmental Abstracts	1998–2021	90	No

Table 1: Methods for paper identification with the date, defined search terms, database, years covered, number of results and if the search had been updated.

The citation information (such as article title, DOI, authors), keywords and abstracts of all papers were exported into a spreadsheet for manual screening. This initial screening excluded papers without any of the following terms in the title, abstract or keywords: '*forest*', 'land degradation neutrality', 'land degradation'. This screening found that 42 papers were not primarily about forests, and 30 did not discuss LDN (Figure 2). Similar terms such as 'desertification' and 'soil degradation' were not considered substitutes for LDN, because 'land degradation neutrality' is a unique and fundamental concept for this study. Moreover, 11 papers were excluded as they discussed LDN from perspectives unrelated to soils or land management, focusing instead on topics such as policy and economics. The process of finding the 12 duplicates after this screening was manual as no referencing software was used. Finally, three papers were irretrievable due to poor or corrupted links, and one was excluded because it was not written in English. This left 53 papers for inclusion in this systematic review.

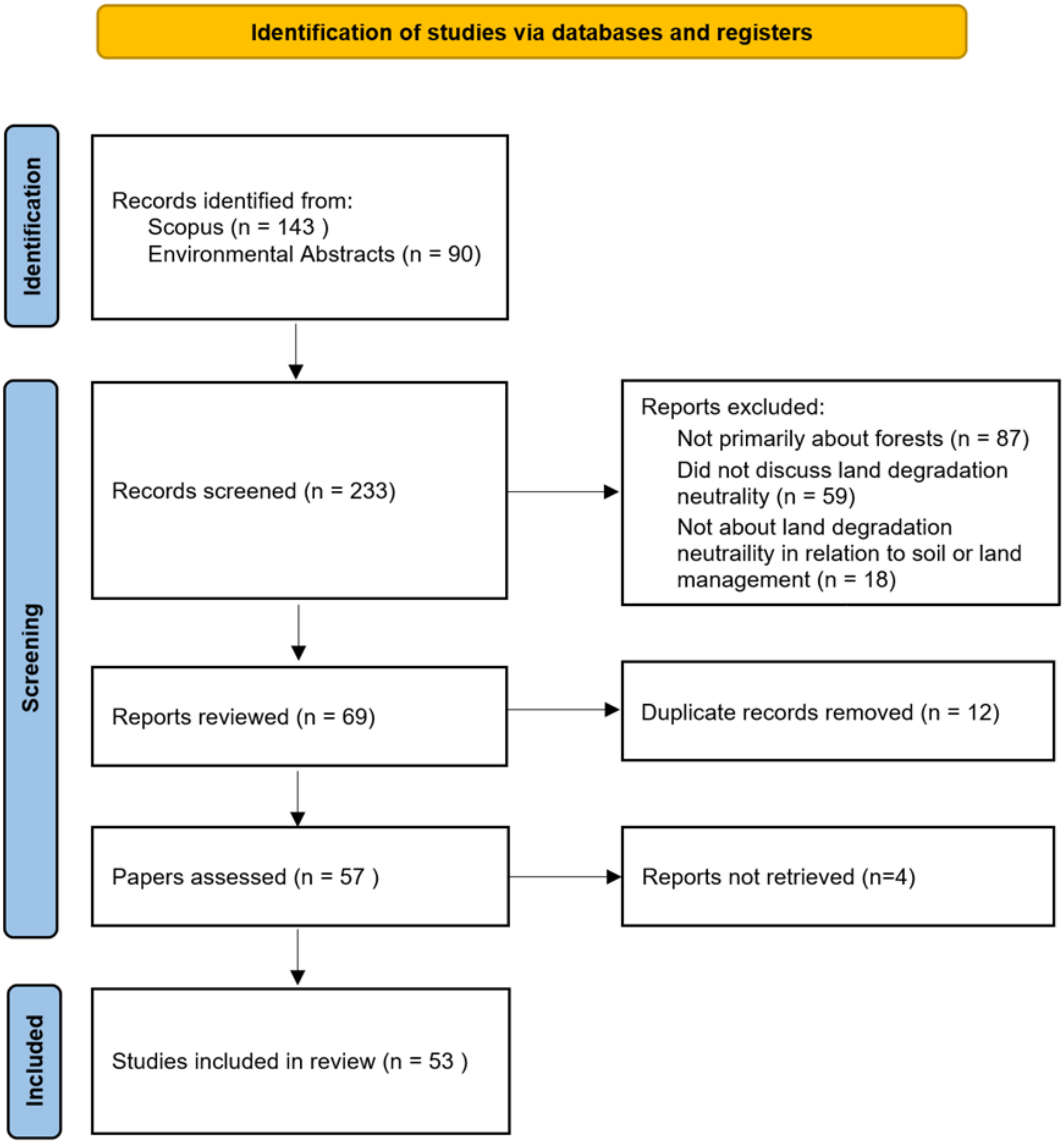

Figure 2: Flowchart describing the identification and screening of studies via Scopus and Environmental Abstracts for this systematic review. 'n' indicates the number of papers falling into any given category. Reports not retrieved indicate papers that appeared in the database but were not located in a journal due to retraction, or those in a language other than English. Adapted from Moher *et al.* (2009).

Data analysis

Literature was reviewed, classified and categorised thematically because quantitative data was limited. Data categorisation was informed by the methods of Lester *et al.* (2020). The following classifications and themes were selected to highlight trends, draw comparisons and capture the current state of FDN:

- Type of article (experiment, literature review, meta-analysis, essay, qualitative analysis, modelling/simulation)
- How the paper measures LDN: indicators (e.g. LULC change, NDVI) and any associated data
- What the paper found the main drivers of land degradation were
- Euclidian area studied
- Country and continent

- Years studied (not necessarily the same as year published)
- Suggestion for the monitoring or achievement of FDN or LDN

Studies were categorised by what they claimed the 'main driver' of land degradation to be and by the indicator of land degradation studies used. These categories were juxtaposed to illuminate the correlation between drivers of land degradation and the indicators measured in studies. Several distinct and highly specific drivers of land degradation were generalised as 'land use change' to correlate with land-use change as a measurable indicator of land degradation. Namely, harvesting and agricultural regimes, increase in demand for agricultural land/agricultural expansion, loss of vegetation cover, land abandonment, land-use pressure and urbanisation were amalgamated for this comparison. Further, conditional analysis was conducted to answer questions such as 'of the papers who mention one factor as a driver of land degradation, how many measure that factor as an indicator of land degradation?'

Results

This systematic review analyses 52 papers, listed in Appendix A. Of these, 25 were classified as experiments, 14 literature reviews, 8 qualitative analyses, 4 meta-analyses and 2 modelling/simulation studies. The main findings from these papers are summarised in Table 2 and Table 3, which enumerate the papers concerned with all listed drivers of LDN and indicators/factors for monitoring, respectively.

Figure 3 presents the distribution of studies by continental focus in a bar graph, overlayed on a map of studied countries. There is a particularly low level of studies in North America, Oceania and South America, which each have two or fewer papers. Moreover, the average length of the study did not vary significantly between continents. The mean study length of all longitudinal studies was 15.4 years (standard deviation (sd) = 8.2). Africa, Asia and Europe recorded averages of 19 (sd = 4, n = 3), 20.75 (sd = 6.4, n = 4) and 14.5 years (sd = 16.3, n = 2), respectively.

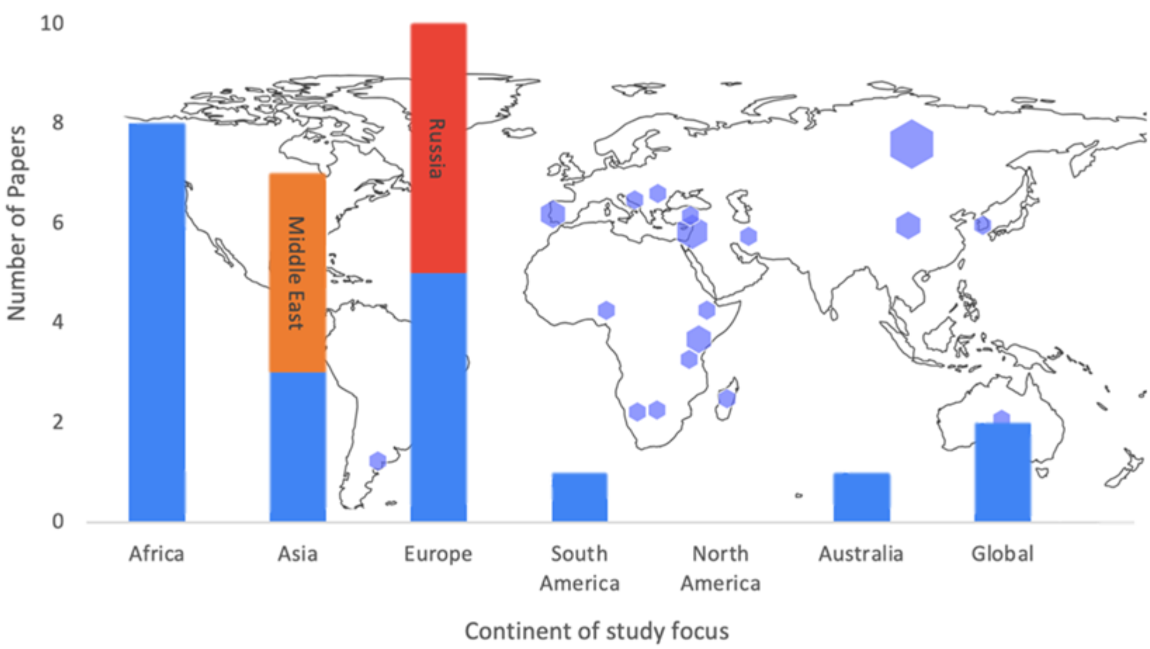

Figure 3: Distribution of studies about FDN focusing on specific locations (n = 29). Russia and the Middle East are highlighted due to their relative significance. Australia was selected over Oceania because it was the only Oceanic country identified in any study.

Figure 4 describes the distribution of indicators for land degradation neutrality in each study. The trio of land cover, net primary productivity (NPP) and soil organic carbon (SOC), are the most abundantly measured with 14 studies. There were nine other studies that measured one or two of these indicators. While some of these factors appear to overlap with the drivers listed in Table 2, Figure 5 provides a more meaningful comparison.

Driver(s) of land degradation	Number of papers which list the driver(s) as a main driver
• Erosion by wind or water	7
• Urbanisation and human activity	6
• Drought and desertification • Pollution (atmospheric and land)	4
• Waterlogging, water degradation and floods • Harvesting and agricultural regimes • Increase in demand for agricultural land/agricultural expansion • Lack of funding to deal with degraded land	3
• Loss of vegetation cover • Chemical or physical soil deterioration (including alkalinisation)	2
• Biological degradation • Land abandonment • Land-use pressure • Salinisation • Acid rain and acidification • Rainfall • Damage caused by fire • Diseases and pests • Compaction	1

Table 2: A summary of the main drivers of land degradation and the number of associated papers. Not all (46 out of 53) papers analysed listed drivers of land degradation or suggested mechanisms.

FDN monitoring or mitigative mechanisms	Recommended or used by # of papers	Criticised by # of papers
• Monitoring land productivity dynamics	7	1
• Monitoring soil organic carbon	4	2
• Measuring NDVI and vegetation cover • Monitoring land cover	4	1
• Improved governance and targeted enforcement of environmental legislation	4	0
• Erosion volumes and modelling • Monitoring nutrient content/fertility/health of soil • Sustainable land management interventions	3	0
• No monitoring method is universally applicable; mechanisms must be specific to location • Integrated and holistic approaches to soil and land management	2	0
• Climate change adaptation programmes • Drought-resistant seeds • Erosion-sensitive soil plantation • Water-saving irrigation systems • Frequent assessment of type, degree, extent and causative factors of soil and land degradation • Evaluating ecosystem services • Modified consumption habits • That a framework for communication between scientists and LDN practitioners needs to be developed • Monitoring ecological degradation trajectories	1	0

Table 3: A summary of the mechanisms suggested for monitoring and defining success with the number of papers recommending and criticising each.

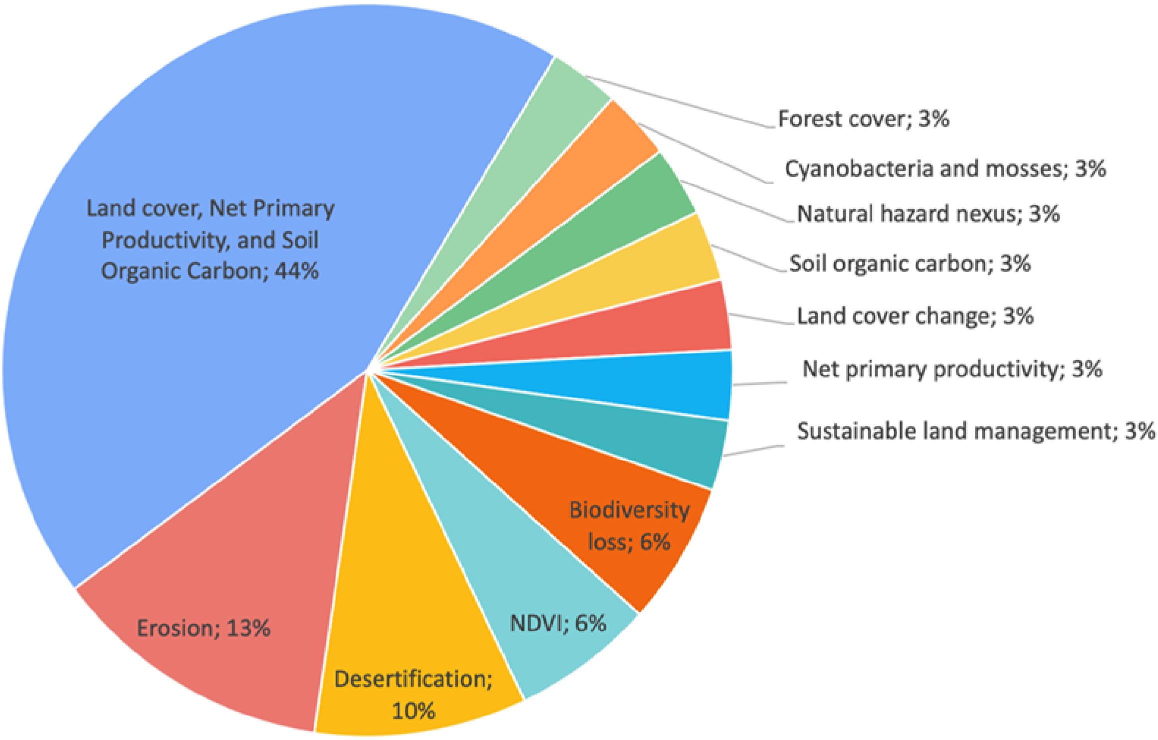

Figure 4: Distribution of the indicators used to measure land degradation neutrality in each applicable study (n = 32).

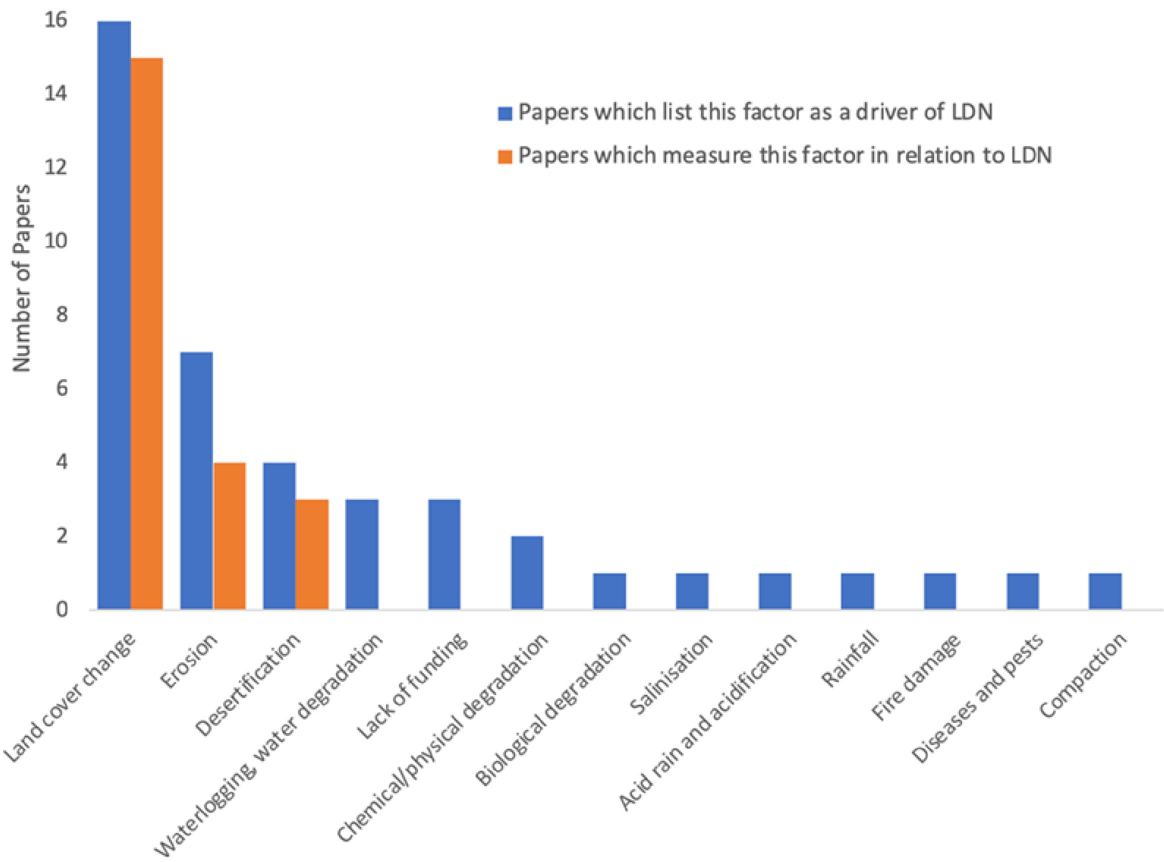

Figure 5: Comparison between papers that ascribed a specific driver to land degradation (n = 46); the number of papers that measured those factors in relation to land degradation neutrality (n = 22).

Figure 5 compares the number of papers that cite a specific driver of LDN against those that simultaneously measured that factor. LULC change, erosion and desertification are the only three factors that were measured but also listed by papers as drivers of LDN. Out of the 16 articles that mention a form of LULC change as a driver of land degradation, 10 measure LULC change as an indicator of land degradation. There were two factors described as drivers of LDN that have not been measured in relation to LDN. Moreover, there were six indicators of LDN not listed as drivers. These were: sustainable land management (n = 1), biodiversity loss (n = 2), net primary productivity (n = 1), soil organic carbon (n = 1), cyanobacteria and mosses (n = 1) and forest cover (n = 1).

Discussion and synthesis

Overview

Our results showed that there are few LDN studies that investigate forests specifically. Of all 53 identified articles discussing LDN, only five had 'forest' in the title, and only one contained the term 'forest degradation neutrality' (Abdullah *et al.*, 2019). This is despite the vulnerability of forests around the world and their provision of extremely high-value ecosystem services, including carbon sequestration, maintenance of the hydrological system and biodiversity (Gibbs *et al.*, 2010: 16736).

However, LDN is a relatively new concept (Figure 1), popularised in 2015 following the international acceptance of the Sustainable Development Goals (Cowie *et al.*, 2018: 26; Kust *et al.*, 2017: 17). While there is currently a deficiency of research into forest LDN, this will probably increase with time. Furthermore, this review's results likely underestimate total FDN research due to the exclusion of non-English language research. Preventing and remediating the degradation of forests is particularly important in the multi-linguistic non-English continents of South America and Africa, which hold the largest remaining areas of contiguous forest in the world, and Asia, whose forest network is extensive but highly fragmented (Haddad *et al.*, 2015). These limitations prevent this review from providing entirely holistic insights into global FDN research.

Grey literature was beyond the scope of this review; however, the following discussion includes LDN publications from the United Nations. The discussion also draws insights from adjacent LDN literature regarding generalised degradation monitoring and remediation to provide depth and context to the otherwise limited pool of English FDN academia.

Land degradation quantification

The United Nations has identified three primary indicators for monitoring LDN:

- Physical land cover class
- Land productivity
- Soil organic carbon stock (SOC)

Tracking these indicators allows for the quantification of natural capital gains compared to losses; however, there are no agreed standards for the exact quantification methods of each indicator. Figure 4 shows that the declaration of these three indicators has had a profound directional impact on FDN research as, cumulatively, they are the most studied component of land degradation. This is also consistent between studies geographically. However, as Figure 3 illustrates, not all continents are represented in FDN research. When the studies only looking at one of these indicators are added to those which examine all three, the measurement of land cover, land productivity and SOC account for 57.6 per cent of all FDN research. When forest cover and desertification are included as subsets of land cover, the amount of research on these indicators rises to 70.1 per cent. This predisposition indicates that the United Nations has a position of influence and authority within the global scientific community as most research has accepted the LDN paradigm proposed by them.

It is emphasised (Akhtar-Schuster *et al.*, 2017: 8–10; Cowie *et al.*, 2018: 31–33; Kust *et al.*, 2018; Kust *et al.*, 2020: 87–88; Teich *et al.*, 2019: 2–3) that the three key indicators prescribed by the United Nations should be supplemented with nation-specific indicators to account for differences in available and valued ecosystem services around the globe. This may account for the vast number of factors being measured and monitored across the field of forest land degradation, listed in Table 3.

Assessing current land conditions is an important first step in achieving land degradation neutrality (Kapović Solomun *et al.*, 2018). The adoption of the 'one out, all out' approach suggested by Orr *et al.* (2017: 100–01) allows for the classification of land as degraded even if only one indicator is in decline; however, this has been criticised for increasing the likelihood of over-inflated land degradation estimates (Cowie *et al.*, 2018: 33). Additionally, despite extensive research in almost all continents (see Figure 3), the lack of standardised indicator quantification techniques, or even an agreed definition of 'degraded land', means that the initial conditions for global degradation cannot be meaningfully compared between studies.

Land cover

The extent of forest land cover is commonly estimated using global datasets, such as satellite imagery from Google Earth and LANDSAT satellites, at varying resolutions to identify varying types of forest cover (Akinyemi *et al.*, 2021). This quantifies land degradation and restoration in units of area, failing to consider the intensity of degradation or ecological quality of forested land. For example, Ptichnikov and Martynyuk (2020: 128–31) used forest-cover percentage as a parameter to measure land cover – with an increase in forest-cover percentage indicating a reduction in degraded land and a decrease suggesting an increase in degraded land.

The area-based quantification approach favoured in the existing research and policy actions would claim LDN to have been achieved if a hectare of old-growth forest was cut down and a hectare of young saplings were planted somewhere else (Ptichnikov and Martynyuk, 2020: 128–31). However, the two are not equivalent in terms of natural capital, as forests take hundreds of years to reach maturity and to provide maximal biodiversity and associated ecosystem services (Lindenmayer and Laurance, 2017: 1437–38). Additionally, habitat fragmentation is particularly harmful to many forest species and is a sign of ecosystem stress (Haddad *et al.*, 2015; Lindenmayer and Laurance, 2017: 1447–49), however, is not recognised in a simplistic net area of degradation model. Therefore, the area-based approach to LDN monitoring is not fit for purpose. These criticisms are recognised by Kust *et al.* (2017: 19) and Morales and Zuleta (2020: 727–30) but are neglected in most research seeking to quantify land degradation. The scientific community must recalibrate how land cover is measured as a parameter of land degradation for research into LDN to be meaningful.

Land productivity

Land productivity is the biological productive capacity of the land, including to produce all the food, fibre and fresh water that sustains humans and ecosystems (Gonzalez-Roglich *et al.*, 2019: 36). Measuring NPP to assess land productivity can provide an understanding of the extent of degradation and the measures necessary to restore the land. To quantify land productivity in forests, the normalised difference vegetation index (NDVI) is often used as a proxy measurement for NPP. For example, Cha *et al.* (2020: 9–10) used NDVI to study forest productivity in Korea. Alternatively, forest productivity can be determined by the quantity of resources created by the forest per time per unit area, including biological productivity and timber productivity (Ptichnikov and Martynyuk, 2020: 132).

Some studies have found that land productivity is particularly useful and effective in identifying subtle differences in sustainable land management practices' impacts, and thereby informing LDN policy (Debonne *et al.*, 2021: 6–8; Gonzalez-Roglich *et al.*, 2019: 36–41). Al Sayah *et al.* (2019: 268) criticised this stance, arguing that NPP can be inferred from land-use changes and is therefore redundant as a land degradation indicator. However, this argument implies an assumption that productivity falls when land is degraded and rises as it is restored, which is not always upheld (Cha *et al.*, 2020: 15–16; Cowie *et al.*, 2018: 30–33).

Soil organic carbon

To measure SOC, a retrospective and forecast calculation of the carbon balance can be implemented in forests, using a carbon budget model to indicate carbon sources and sinks (Ptichnikov *et al.*, 2019). Alternatively, SOC may be estimated using data from above-ground and below-ground carbon stocks, as carbon levels at depth can provide insight into the health of soils and, consequently, the fertility and level of degradation in the land (Cha *et al.*, 2020: 9–10).

The rate and direction of SOC changes vary greatly around the world, as highlighted by Figure 6, with the most significant SOC losses occurring in North America, Russia, China and Brazil (Prăvălie *et al.* 2021: 5). This systematic review identified five articles specifically addressing LDN and SOC in Russia, which indicates that at least the scientific community is aware of the problem in this area. However, it is alarming that there were no such studies centred in North America, which is experiencing the greatest long-term SOC losses globally (Prăvălie *et al.*, 2021: 5).

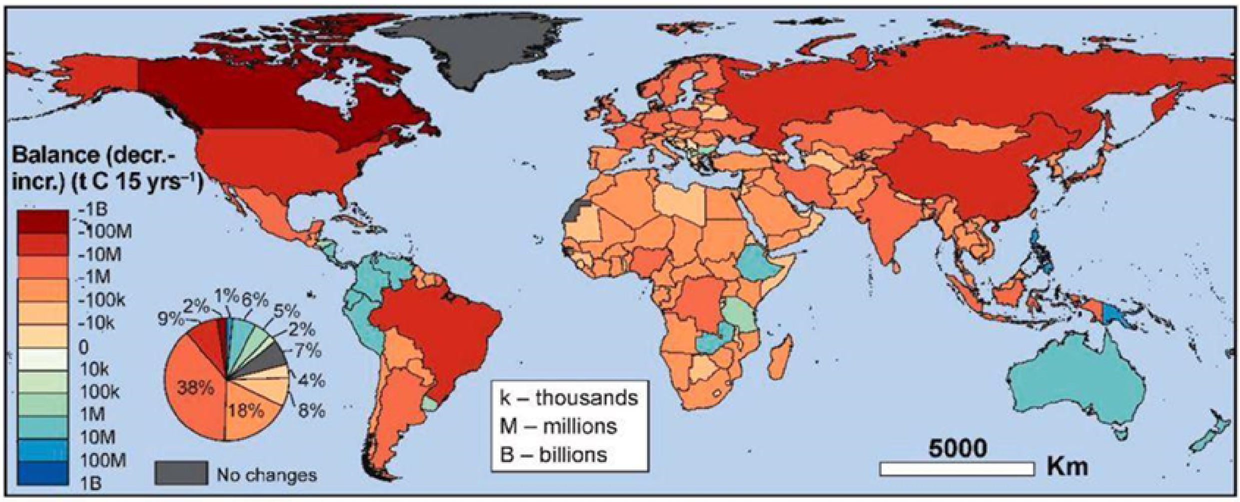

Figure 6: The distribution of absolute SOC changes throughout the countries of the world in terms of balance between total decreases and increases. Reproduced from Prăvălie *et al.* (2021: 5) with kind permission from the lead author.

Reaching a consensus

The inconsistency of models, datasets and methods of measurement found by this review are issues that make synthesising evidence from multiple studies very difficult (Hennessy *et al.*, 2022; Kadykalo *et al.*, 2020) and contribute to the high levels of research waste seen in some disciplines (Glasziou and Chalmers, 2018;

Yordanov *et al.* 2018). Without synthesis, policy and management decisions often rely on the results of individual studies or select expert opinions, which undermines policy efficacy and can erode public trust in research (Cairney, 2016, 2021). However, FDN is a young field of research. If a consensus on FDN metrics can be reached soon, the field may avoid these pitfalls.

Reed *et al.* (2022) successfully facilitated such a consensus for the monitoring of global peatlands. The first effort of its kind, Reed *et al.* took a framework commonly used in the medical science community to collaboratively identify, evaluate and prioritise 'core domain sets' of research variables, and applied that framework to peatland research. Their work serves as a case study for determining what to measure and how to measure it in broader environmental contexts, including LDN and FDN.

This review adds to the increasing calls for data collection and reporting to be globally standardised (Gurevitch *et al.,* 2018; Nichols *et al.*, 2021), specifically with reference to forest degradation. The framework recommended by Reed *et al.* (2022) may prove an effective first step in achieving such standardisation.

Drivers of land degradation

Forest degradation is driven by a combination of natural and anthropogenic factors such as climate change, urbanisation and agricultural pressure, factors that cumulatively result in erosion, desertification, pollution and deforestation (Kissinger, 2012: 5–16). Anthropogenic drivers in particular are placing unprecedented demands on agricultural and natural resources as global populations increase, causing forest degradation to accelerate in line with accelerating resource consumption (Ramankutty *et al.*, 2008: 14; Rockström *et al.*, 2017: 4–6).

The existing literature surrounding land degradation is focused more on its symptoms than root causes, and the collective knowledge is highly disparate. The ambiguity of the term 'land degradation neutrality', has led to a vast array of variables being researched and measured, as shown in Tables 2 and 3, and Figure 4, and no clear consensus is evident. While there were 4 meta-analyses and 14 literature reviews found, few reckoned with how to prioritise the study of the many dynamic and varied factors involved with LDN, including erosion, desertification, pollution and deforestation. Additionally, only 7 of the 53 reviewed papers discussed drivers of land degradation, and of the 19 different drivers posited within these only 3 are measured, as shown in Figure 5. Thus, it is clear that the drivers of land degradation are under-researched.

A weak understanding of why land degradation occurs may hamper the pursuit of LDN. The current glut of research measuring and discussing the effects of degradation rather than its root causes and drivers have resulted in a strong understanding of the problem, but not how to fix it. This is analogous to understanding the velocity of a stream of water, but not knowing where the tap is or how to turn it off, presenting a challenge for decision-makers and policymakers seeking to reconcile these complexities into effective action towards LDN.

The chemical, physical, biological and economic complexities of forested land make any meaningful remediation process expensive and time-consuming. Therefore, prevention of forest degradation is a more effective long-term strategy than remediation. To achieve this, understanding the impacts and indicators of LDN alone are insufficient. There now exists an opportunity to stunt the effects of land degradation by focusing more on its drivers and seeking systemic change to address these underlying causes.

Conclusion

There are many indicators of land degradation. The most common and universal of these to have been measured in existing literature are the indicators prescribed by the United Nations Convention to Combat Desertification (2015): land cover, land productivity and soil organic carbon stocks. When other factors such as soil erosion or nutritional content are particularly relevant to a specific region's climate or environmental conditions, these should also be monitored as indicators. Under the current paradigm, 'degraded land' is that for which at least one indicator is in decline, 'stable land' is that which exhibits no change in any indicator, and 'land under restoration' is that experiencing an increase in at least one indicator and no decreases. Therefore, to answer the question posed by this review, we shall know when we achieve land degradation neutrality with respect to forests because the net area of land considered as undegraded 'forest' in 2015 – the year that the Sustainable Development Goals were agreed – will be the same as that in the target year of 2030. However, there are concerns that this approach could overestimate the area of degraded land, neglect the impacts of land cover fragmentation and inappropriately balance the magnitudes of degradation severity and rehabilitative success.

If we are to assess whether LDN has been achieved by 2030, and in particular LDN of forests, this systematic review has identified the following knowledge gaps that will need to be addressed.

Firstly, and most urgently, a standardised approach must be developed to quantify the three land degradation indicators and common supplementary indicators. This will allow meaningful comparison between international studies, which currently use different methodologies. These standard methodologies should also account for the relative magnitude of degradation and rehabilitation rather than treating all degraded areas and all restored areas as having equal and opposite values. This will require greater research into LDN in the forest context, as the area lacks the expertise required to fully understand how different forest types should be prioritised and valued within a magnitude-inclusive system. An effective framework to determine these variables is the 'core domain sets' workshop approach currently common to medical science, and recently pioneered in environmental science. The most effective forum for the implementation of this framework and subsequent dissemination of standardised LDN methodologies may be the United Nations, as the widespread adoption of their published LDN indicators has proven them to be extremely influential in this field.

Secondly, the amount and magnitude of degraded land as of 2015 must be determined in accordance with the new standardised system as a baseline for comparison. This will require large-scale global collaboration, including in North America, Oceania and South America, which have thus far been largely neglected in LDN literature.

Finally, further investigation must be conducted into the drivers of land degradation and how they may be prevented, in all contexts and socio-economic systems. Without this crucial research, we may perfectly quantify and measure ecological decline but will be powerless to change it.

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List of figures

List of tables

Appendix A – Reviewed articles

Authors	**Title**	Year
Adessi A., De Philippis R., Rossi F.	Drought-tolerant cyanobacteria and mosses as biotechnological tools to attain land degradation neutrality	2021
Akhtar-Schuster M., Stringer L. C., Erlewein A., Metternicht G., Minelli S., Safriel U., Sommer S.	Unpacking the concept of land degradation neutrality and addressing its operation through the Rio Conventions	2017
Akinyemi F. O., Ghazaryan G., Dubovyk O.	Assessing UN indicators of land degradation neutrality and proportion of degraded land for Botswana using remote sensing based national level metrics	2021
Al Sayah M. J., Abdallah C., Der Sarkissian R., Abboud M.	A framework for investigating the land degradation neutrality – Disaster risk reduction nexus at the sub-national scales	2021
Al Sayah M. J., Abdallah C., Khouri M., Nedjai R., Darwich T.	Application of the LDN concept for quantification of the impact of land-use and land cover changes on Mediterranean watersheds – Al Awali basin – Lebanon as a case study	2019
Al Sayah M. J., Abdallah C., Khouri M., Nedjai R., Darwich T.	On the use of the Land Degradation Neutrality concept in mediterranean watersheds for land restoration and erosion counteraction	2021
Albaladejo J., Díaz-Pereira E., de Vente J.	Eco-Holistic Soil Conservation to support Land Degradation Neutrality and the Sustainable Development Goals	2021
Allen C., Metternicht G., Verburg P., Akhtar-Schuster M., Inacio da Cunha M., Sanchez Santivañez M.	Delivering an enabling environment and multiple benefits for land degradation neutrality: Stakeholder perceptions and progress	2020
Amiraslani F., Caiserman A.	Multi-stakeholder and multi-level interventions to tackle climate change and land degradation: The case of Iran	2018
Baumber A., Berry E., Metternicht G.	Synergies between Land Degradation Neutrality goals and existing market-based instruments	2019
Cha S., Kim C.-B., Kim J., Lee A. L., Park K.-H., Koo N., Kim Y. S.	Land-use changes and practical application of the land degradation neutrality (LDN) indicators: a case study in the subalpine forest ecosystems, Republic of Korea	2020
Chappell A., Webb N. P., Leys J. F., Waters C. M., Orgill S., Eyres M. J.	Minimising soil organic carbon erosion by wind is critical for land degradation neutrality	2019
Chasek P., Akhtar-Schuster M., Orr B. J., Luise A., Rakoto Ratsimba H., Safriel U.	Land degradation neutrality: The science-policy interface from the UNCCD to national implementation	2019
Cowie A. L., Orr B. J., 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.	Land in balance: The scientific conceptual framework for Land Degradation Neutrality	2018
Cowie A. L., Waters C. M., Garland F., Orgill S. E., Baumber A., Cross R., O'Connell D., Metternicht G.	Assessing resilience to underpin implementation of Land Degradation Neutrality: A case study in the rangelands of western New South Wales, Australia	2019
Crossland M., Winowiecki L. A.,	Implications of variation in local perception of degradation and	2018

Pagella T., Hadgu K., Sinclair F.	restoration processes for implementing land degradation neutrality	
Dallimer M., Stringer L. C.	Informing investments in land degradation neutrality efforts: A triage approach to decision making	2018
Debonne N., van Vliet J., Metternicht G., Verburg P.	Agency shifts in agricultural land governance and their implications for land degradation neutrality	2021
del Barrio G., Sanjuán M. E., Martínez-Valderrama J., Ruiz A., Puigdefábregas J.	Land degradation means a loss of management options	2021
Erşahin S.	A method for calculating land degradation neutrality	2020
García C. L., Teich I., Gonzalez-Roglich M., Kindgard A. F., Ravelo A. C., Liniger H.	Land degradation assessment in the Argentinean Puna: Comparing expert knowledge with satellite-derived information	2019
Gichenje H., Muñoz-Rojas J., Pinto-Correia T.	Opportunities and limitations for achieving land degradation-neutrality through the current land-use policy framework in Kenya	2019
Gichenje H., Pinto-Correia T., Godinho S.	An analysis of the drivers that affect greening and browning trends in the context of pursuing land degradation-neutrality	2019
Gonzalez-Roglich M., Zvoleff A., Noon M., Liniger H., Fleiner R., Harari N., García C.	Synergizing global tools to monitor progress towards land degradation neutrality: Trends.Earth and the World Overview of Conservation Approaches and Technologies sustainable land management database	2019
Grainger A.	Is Land Degradation Neutrality feasible in dry areas?	2015
Hüttl R. F., Schneider B. U.	Forest ecosystem degradation and rehabilitation	1998
Ifejika Speranza C., Adenle A., Boillat S.	Land Degradation Neutrality – Potentials for its operationalisation at multi-levels in Nigeria	2019
Jiang C., Yang Z., Wang X., Dong X., Li Z., Li C.	Examining the reversal of soil erosion decline in the hotspots of sandstorms: A non-linear ecosystem dynamic perspective	2021
Jiang C., Zhang H., Zhao L., Yang Z., Wang X., Yang L., Wen M., Geng S., Zeng Q., Wang J.	Unfolding the effectiveness of ecological restoration programs in combating land degradation: Achievements, causes and implications	2020
Kapović Solomun M., Barger N., Cerda A., Keesstra S., Marković M.	Assessing land condition as a first step to achieving land degradation neutrality: A case study of the Republic of Srpska	2018
Kust G., Andreeva O., Cowie A.	Land Degradation Neutrality: Concept development, practical applications and assessment	2017
Kust G., Andreeva O., Lobkovskiy V., Telnova N.	Uncertainties and policy challenges in implementing Land Degradation Neutrality in Russia	2018
Kust G. S., Andreeva O. V., Lobkovskiy V. A.	Land Degradation Neutrality: the Modern Approach to Research on Arid Regions at the National Level	2020
Morales N. S., Zuleta G. A.	Comparison of different land degradation indicators: Do the world regions really matter?	2020
Nijbroek R., Piikki K., Söderström M., Kempen B., Turner K. G.,	Soil organic carbon baselines for land degradation neutrality: Map accuracy and cost tradeoffs with respect to complexity in	2018

Hengari S., Mutua J.	Otjozondjupa, Namibia	
Pacheco F. A. L., Sanches Fernandes L. F., Valle Junior R. F., Valera C. A., Pissarra T. C. T.	Recent studies on land degradation assessment at local, regional and global scales were preferentially based on translations of Normalized Difference Vegetation Index (NDVI) into land degradatio, but also resort to MultiCriteria Analyses that combine risk factors in various ways, or describe land degradation neutrality as sustainable trade-off between food production and one or more of other ecosystem services	2018
Pastor A. V., Nunes J. P., Ciampalini R., Koopmans M., Baartman J., Huard F., Calheiros T., Le-Bissonnais Y., Keizer J. J., Raclot D.	Projecting future impacts of global change including fires on soil erosion to anticipate better land management in the forests of NW Portugal	2019
Pena S. B., Abreu M. M., Magalhães M. R., Cortez N.	Water erosion aspects of land degradation neutrality to landscape planning tools at national scale	2020
Prăvălie R., Nita I.-A., Patriche C., Niculiță M., Birsan M.-V., Roșca B., Bandoc G.	Global changes in soil organic carbon and implications for land degradation neutrality and climate stability	2021
Ptichnikov A. V., Karelin D. V., Kotlyakov V. M., Pautov Y. A., Borovlev A. Y., Kuznetsova D. A., Zamolodchikov D. G., Grabovsky V. I.	Indicators in Estimation of Land Degradation Neutrality for Russian Boreal Forests	2019
Ptichnikov A. V., Martynyuk A. A.	Adaptation of International Indicators of Land Degradation Neutrality for the Assessment of Forest Ecosystems in Arid Conditions in Russia	2020
Quatrini S., Crossman N. D.	Most finance to halt desertification also benefits multiple ecosystem services: A key to unlock investments in Land Degradation Neutrality?	2018
Reith J., Ghazaryan G., Muthoni F., Dubovyk O.	Assessment of land degradation in semiarid Tanzania-using multiscale remote sensing datasets to support sustainable development goal 15.3	2021
Safriel U.	Land degradation neutrality (LDN) in drylands and beyond – where has it come from and where does it go	2017
Schulze K., Malek Ž., Verburg P. H.	How will land degradation neutrality change future land system patterns? A scenario simulation study	2021
Sciortino M., De Felice M., De Cecco L., Borfecchia F.	Remote sensing for monitoring and mapping Land Productivity in Italy: A rapid assessment methodology	2020
Sietz D., Fleskens L., Stringer L. C.	Learning from Non-Linear Ecosystem Dynamics Is Vital for Achieving Land Degradation Neutrality	2017
Stavi I., Lal R.	Achieving Zero Net Land Degradation: Challenges and opportunities	2015
Ştefănescu M., Ciuvăț L. A.	Land degradation neutrality – A new pathway towards sustainable development in Romania	2018
Teich I., Roglich M. G., Corso M. L., García C. L.	Combining Earth observations, cloud computing and expert knowledge to inform national level degradation assessments in support of the 2030 development agenda	2019
Tsvetnov E. V., Makarov O. A.,	The Role of Soils in Land Degradation Assessment: A Review	2021

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Glossary

Ecosystem services: The benefits provided to humans by healthy ecosystems, including food production, water, soil and air quality regulation, soil formation, climate regulation, fauna habitats, and spiritual/cultural services.

Forest degradation neutrality (FDN): The state whereby the total amount and quality of forests within a given area remains stable or increases over time.

Grey literature: :Information which is not-peer reviewed and has been produced by parties who are not publishers. Grey literature includes government papers, business reports and academic writings not published in a journal or book.

Land degradation: A loss of either productivity or soil organic carbon, or a change in land use/land cover that negatively impacts the ability of a given area of land to provide ecosystem services.

Land degradation neutrality (LDN): The state whereby the total amount and quality of land-based natural capital within a given area remains stable or increases over time.

Natural capital: Natural resources such as air, soil, water and living organisms necessary to support ecosystem functions and services.

Net primary productivity (NPP): The energy fixed by plants from the sun and soil, minus the energy lost through plant respiration.

Normalised difference vegetation index (NDVI): A quantification of the density of vegetation based on measuring the difference between near-infrared light (strongly reflected by vegetation) and red light (strongly absorbed by vegetation) reflected from the land.

Positive feedback cycle: An unstable process that exacerbates the effect of a small disturbance.

Primary productivity: The rate at which primary producer organisms create biomass from energy and inorganic substrates.

Soil organic carbon (SOC): The carbon content of organic matter in soils, used as a proxy measurement for soil organic matter, which is vital for soil fertility.

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