frontiers | Frontiers in Forests and Global Change

TYPE Mini Review
PUBLISHED 16 July 2024
DOI 10.3389/ffgc.2024.1398864

OPEN ACCESS

EDITED BY
Gopal Shukla,
North Eastern Hill University, India

REVIEWED BY
Shaon Kumar Das,
The ICAR Research Complex for North Eastern Hill Region (ICAR RC NEH), India
Sumit Chakravarty,
Uttar Banga Krishi Viswavidyalaya, India

*CORRESPONDENCE
M. Amritha Gunawardena
✉ amrithagunawardena@gmail.com

RECEIVED 10 March 2024
ACCEPTED 26 June 2024
PUBLISHED 16 July 2024

CITATION
Gunawardena MA, Lokupitiya E and Gunawardena P (2024) Land degradation neutrality and carbon neutrality: approaches, synergies, and challenges.
Front. For. Glob. Change 7:1398864.
doi: 10.3389/ffgc.2024.1398864

Land degradation neutrality and carbon neutrality: approaches, synergies, and challenges

M. Amritha Gunawardena[1]*, Erandathie Lokupitiya[1] and Prasanthi Gunawardena[2]

[1]Department of Zoology and Environment Sciences, University of Colombo, Colombo, Sri Lanka, [2]Department of Forestry and Environmental Science, University of Sri Jayewardenepura, Nugegoda, Sri Lanka

Land is being degraded rapidly worldwide. United Nations Convention to Combat Desertification in 2015 has invited countries to formulate voluntary targets to achieve Land Degradation Neutrality (LDN). Under the Paris Agreement, a legally binding international treaty adopted in 2015, the world is transitioning toward Carbon Neutrality (CN) with more mitigation actions. This paper intended to review the concepts of land degradation, LDN along with CN emphasizing the degradation types, approaches, models available to analyze, synergies, economic aspects and challenges. The review explores approaches and models available for achieving LDN and CN which are both synergistic, economically efficient and could overcome the common challenges. Land degradation has to focus beyond the traditional definitions to incorporate more persistent and the difficult to restore degradation causes. Such complex land degradation requires specialized LDN approaches. The level of degradation and restoration progress could be analyzed using a variety of modeling approaches including economic models. Approaches for LDN and CN can bring significant synergies for each other. The approach proposed by the present study will provide a logical flow for decision-making while minimizing time and effort and avoiding a piecemeal approach. The approach therefore maximizes the output in relation to the inputs thus enhancing sustainability.

KEYWORDS

land degradation, climate change, land degradation neutrality, carbon neutrality, synergy

1 Introduction

The modern agricultural, industrial and urban development implies that the land is continuously being degraded and that degradation could sometimes stay as a permanent state. Land degradation is caused by a variety of reasons and traditionally associated with soil erosion (Chalise et al., 2019) and desertification (Briassoulis, 2019). However, increasing levels of chemicals and pollutants in the environment means that the degradation has wider spatial and temporal dimensions. The nature of the materials that are added to the environment, their behavior and sensitivity of the receiving environment will determine the severity of the degradation, and the possibility of recovery. The level of degradation could be analyzed using a variety of models ranging from simple map-based models to complex models that require multiple data. The feasibility of recovery or restoration could be assessed by various economic tools. Degradation that is difficult to recover, unrecoverable or unrestorable implies a large economic cost.

Emission of higher levels of greenhouse gases (GHGs) have increased the humanity's vulnerability to climate change. Global actions have proposed mechanisms for carbon neutrality (CN) which are nicely linked with the land degradation neutrality (LDN). Assessment and modeling of carbon neutralizing options, their feasibility from both technical and economic viewpoint will enable us to recognize cost minimizing synergies for achieving LDN and CN. Although land degradation is a local issue carbon dioxide is a global pollutant. Properly implemented LDN actions therefore generate global benefits. It is therefore worthwhile finding the matching pairs that could achieve both LDN and CN.

The study intends to understand the degradation types at a deeper level to recognize easy to remediate degradation types and more persistent degradation types. This knowledge is further enhanced by models that predict future outcomes resulting from the degradation. Among the options available for achieving LDN and CN, the ones that maximizes the economic efficiency can be chosen while understanding challenges. This approach will provide a logical flow in making the decision while minimizing the time and effort. The approach therefore maximizes the output in relation to the inputs thus enhancing sustainability.

2 Methodology

Literature was searched using variety of search engines such as google scholar and ScienceDirect with search words of the main topic including Land Degradation, Land Degradation Neutrality and Carbon Neutrality. Then for each term the following search words were added; definitions, global actions, approaches, models, economics, challenges. Then combinations of main topics including LDN and CN were searched with the word synergy. After screening the abstracts and contents of the articles, most significant sources of information were selected and reviewed for analysis and synthesis. Only the papers published in indexed peer-reviewed journals that are included in Scopus database and book chapters from recognized publishers were used. Eighty-four publications were found which were relevant. Non-English articles and articles that do not focus on the goal of the study were excluded. Then the results obtained from the above search were synthesized, edited and presented under each topic. Supplementary Figure S1 summarizes the review protocol.

3 Land degradation and its impact on nature and humans

Land degradation is defined as a "reduction or loss of biological or economic productivity and complexity of agroecological systems as a consequence of land use, or from one or more processes that may arise from human activities" (UNCCD, 2024). Land degradation exerts severe negative impacts on global and regional economic and social development and food security (Deng and Li, 2016; Chan et al., 2023). Highly degraded areas cover about 29% of global land area which is home to about 3.2 billion people (Le et al., 2016). Agricultural lands and natural habitats are degraded due to various forms of land degradation. For example, livelihood of two-third of the population of India, are vulnerable due to land degradation (Mythili and Goedecke, 2016) and land degradation hotspots cover about 51% of land area in Tanzania and 41% in Malawi (Kirui, 2016).

Analysis of causes of land degradation and their extents (Mythili and Goedecke, 2016) adopting multidimensional perspective (Prăvălie, 2021) help to design suitable policies to overcome the degradation. Traditionally, land degradation is explained in relation to erosion by water and by wind, salinization, and soil acidification and vegetation degradation. However, more severe and permanent land degradation could result from land pollution from a variety of chemicals and plastic. Land degradation due to chemicals is a complex phenomenon which requires understanding of system dynamics (Gunawardena, 2022).

Pesticides including insecticides, fungicides, herbicides, rodenticides can lead to sterile soils (UNCCD, 2017; Tang et al., 2021). These may also lead to depletion of soil biodiversity (Beaumelle et al., 2023) and overall biodiversity in the landscape due to impairment of pollination function (Hashimi et al., 2020). In addition, mixtures of insecticides and herbicides could bring significant synergistic ecotoxicological effects to the earthworms (Uwizeyimana et al., 2017) in the presence of heavy metals. Heavy metals could bring a variety of negative impacts on soil organisms (Liu et al., 2021) including earthworms (Morgan and Morgan, 1992; Fourie et al., 2007).

Persistent organic pollutants (POPs) resulting from industrial activities may be either directly dumped onto the land or land filled. Sludge applications to crops is another source of POPs resulting from industrial wastewaters (Arvaniti and Stasinakis, 2015). This may lead to contamination of ecosystems, food chains, and water. The damages resulting from landfills could be severe with large loads of contaminants with future risk that may last for centuries (Weber et al., 2011) due to their capacity to bioconcentrate, bioaccumulate, and biomagnify. In addition, electronic waste recycling sites can also generate complex mixtures of dioxin-related compounds which can contaminate surface soils (Manz et al., 2001).

Mining activities, for example, coal (Dhyani et al., 2023), mineral and metal mining cause land degradation. Increasing mining efforts lead to generation of higher waste quantities per unit of useful product which is disposed into tailing dumps (Slipenchuk et al., 2019). Adverse effects of plastics and microplastics in soils (Rillig, 2012) are likely due to dumping of disused or abandoned plastic, municipal wastewater effluents, landfilling with sewage sludge and plastic used in agricultural activities (Chae and An, 2018; Hale et al., 2020). Furthermore, microplastics can be bioaccumulated among organisms (Yang et al., 2023).

Deforestation leads to land degradation and water depletion due to the increased levels of soil erosion and associated nutrient depletion and sediment transport (Chan et al., 2023). Land degradation could result in significant loss of ecosystem services. Millennium ecosystem assessment report defines land degradation as the long-term loss of ecosystem services (Nkonya et al., 2016a).

4 International actions and multilateral environmental agreements related to land and climate change

The 1992 Earth Summit initiated three Rio Conventions on climate change, desertification, and biodiversity. The United Nations Framework Convention on Climate Change (UNFCCC) aims to prevent "dangerous" human interference with the climate system (UNFCCC, 2024). The United Nations Convention to Combat Desertification (UNCCD) is dedicated to combatting desertification and mitigating the impacts of drought in countries facing severe desertification or drought conditions (UNCCD, 1994).

Under the Paris Agreement, a legally binding international treaty adopted in 2015, the world is transitioning toward CN with more mitigation actions. In October 2015, the 12th Conference of the Parties (COP12) of the UNCCD proposed a definition for land degradation neutrality (LDN). In 2017, an LDN Scientific Conceptual Framework was developed and endorsed by UNCCD Member States (Cowie et al., 2018).

There have been several chemical-related multilateral environmental agreements (MEAs) that have a relevance to land degradation including the Basel Convention on the control of transboundary movements of hazardous wastes and their disposal, Rotterdam Convention on the prior informed consent procedure for certain hazardous chemicals and pesticides in international trade and Stockholm Convention on persistent organic pollutants. However, the linkages of these conventions with land degradation have been less obvious.

During the UN Summit for the adoption of the post-2015 development agenda, an agreement on set of 17 Sustainable Development Goals (SDGs) (UN, 2015) was made. Under SDG 15 Life on Land, target 15.3 intends to achieve a land degradation neutral world while target 2.4 of SDG 2 encourages resilient agricultural practices and gender equality over land resources is emphasized under Target 5.a. Achieving LDN increases ecosystem services and improves soil quality, contributing to several other SDGs, including SDG 3 (good health and wellbeing), SDG 5 (gender equality), SDG 6 (clean water and sanitation), SDG 11 (sustainable cities and communities), SDG 12 (responsible consumption and production), SDG 13 (climate action), SDG 14 (life below water), and SDG 15 (life on land) (Feng et al., 2022). It is important to note here that each SDG has synergies and trade-offs with other SDGs. On the other hand, the key MEAs related to land and climate change are reflected in several SDGs. For example, UNCCD is linked to seven SDGs, UNFCCC is linked to nine SDGs, and chemical conventions are linked to six SDGs (UNEP, 2016).

5 Land degradation neutrality

It is important to discuss the causes of land degradation and also how to neutralize the impacts. Land degradation will effectively reduce the useful amount of land available for ecosystems, biodiversity and other living beings. For example, built up land or urban infrastructure implies permanent loss of land and their ecosystem services (Maes et al., 2015) where the concept of LDN is not applicable or not achievable. Urban vegetation including vertical gardens and roof top gardens may bring some nature that will improve the greenery, but the loss of soil or permanent cover of soil will lead to permanent loss of primary ecosystem services such as soil formation (Jayakody et al., 2023). Increasing built-up land and pavements and disturbed landscapes will reduce the water that is infiltrated to the ground and increase the runoff and degrade further the quality of the water that is added to the waterways (Kriech and Osborn, 2022).

Other transformed landscapes, such as agricultural and plantation areas, when managed under organic conditions, imply higher ecosystem services. However, under chemically intensive conditions, they imply a permanent loss of ecosystem services (Kremen and Miles, 2012) and non-achievement of LDN, since such chemicals act as stock pollutants and tend to stay in the soil for a long period of time. When the soils are contaminated with POPs, such soils cannot be restored because effective removal of the POPs is extremely costly. Achieving LDN in such contexts is therefore a non-attainable goal. Certain pesticides that are classified under POPs could have contaminated large extents of tropical soils before their ban under the Stockholm Convention.

Materials considered as chemically inactive such as plastic will be detrimental to earthworms and other soil microorganisms. Microplastics and nanoplastics contaminated soil cannot be reversed to the original situation and currently most agricultural soils are faced with this problem due to the higher and higher use of plastic-based materials in agricultural areas (Serrano-Ruiz et al., 2021; Scopetani et al., 2022). Such soils will be in a permanent degraded state and any productivity will have to be achieved with very high level of externally supplied inputs yet with uncertainty in outcomes. Extremely high costs associated with of such type of LDN may not be cost effective given the limited resources available in low-income tropical countries. It is worth noting here that the investments in sustainable land management (SLM) have been low in the developing countries where the impact of land degradation are most crucial (Chen et al., 2022).

Even the most common type of land degradation caused by soil erosion is assumed to be recoverable when the replacement is done for the lost nutrients, organic matter and macro and microorganisms (Lal, 2015) known to occur in the original soil. However, due to uncertainty of such information, it may not be fully recovered. For example, information on types and numbers of soil microorganisms present in a soil is extremely difficult to find and the replacement will be incomplete.

6 Carbon neutrality, the need and approaches

Carbon neutrality, a state of net zero carbon emission is proposed to be achieved with decarbonization strategies. A hierarchical approach has been defined to achieve this. The first in the list is avoiding carbon intensive actions, the next is reduction of carbon emitting activities by efficiency improvements. Replacing carbon intensive activities with alternatives is the third option and finally, offsetting any leftover emissions that are unavoidable is suggested (Finkbeiner and Bach, 2021). Carbon neutrality can be defined for a country, company, product, activity, or at individual level and the total emissions emitted directly or indirectly has to be balanced by offset or removal mechanisms (UNFCCC, 2021). Carbon neutrality has to be achieved involving all sectors of the economy (Nkonya et al., 2016b). Figure 1 indicates options available for LDN and CN and their interrelations.

Proper forest management can effectively improve the carbon storage of the forests. Examples include different rotation periods (Hektor et al., 2016), use of different tree species especially those with high carbon storage potentials (de Morais et al., 2019), enriching with lianas and climbers (Shukla et al., 2020) and different forest management measures that could improve soil organic carbon (Ma et al., 2021). Agricultural crops when grown under organic conditions,

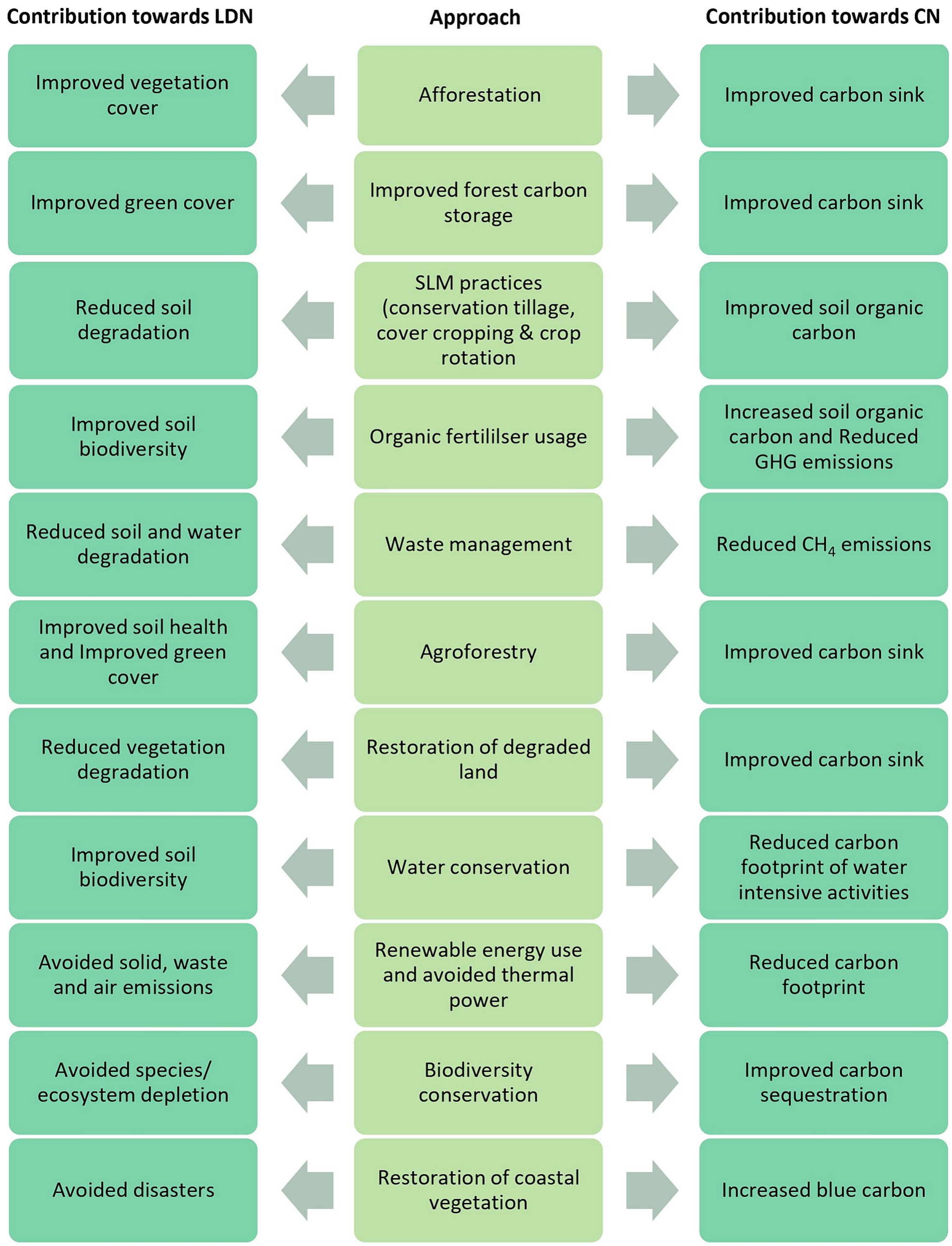

FIGURE 1
Approaches to achieve LDN and CN.

will bring both LDN and CN benefits. Options such as agroforestry will improve soil health, carbon sinks and bring additional benefits to the farming communities. Water conservation will improve soil biodiversity thus generating positive effects toward LDN while reducing carbon footprints. Use of renewable energy will also reduce the carbon footprint with lesser emissions deposited in land thus minimizing land pollution. Moreover, to achieve net-zero carbon emissions and sustainable development, sequestration in terrestrial and marine ecosystems must be promoted (Cheng, 2020). In addition, deploying negative-emission technologies at large scale, promoting regional low-carbon development and establishing a nationwide "green market" have been proposed for China (Liu et al., 2022). Carbon sink technology is another option for CN. Carbon sink refers to the process of absorbing carbon dioxide in the atmosphere through afforestation, vegetation restoration and other measures. It generally consists of terrestrial carbon sinks and ocean carbon sinks (Wu et al., 2022).

The above options indicate range of opportunities with differing efficiency in addressing LDN and CN. As such, a combination of approaches would be useful in addressing land degradation and carbon emission issues in a given socioeconomic and ecological landscape.

Increment of soil organic carbon (SOC) sequestration is considered as a possible solution to mitigate climate change as well as to reduce the land degradation. A study done by Minasny et al. (2017) reports SOC stocks from 20 regions in the world. The top 1 m layer of soil contains about 600 Gt of carbon and if SOC stocks are increased by 0.4%, it can mitigate about 30% of global GHG emission. The study reports mean SOC stocks for each country and how much SOC sequestration rate is required to achieve the 0.4% initiative and also it reports opportunities available to sequester more carbon. This finding has been translated into an initiative named "4 per mille Soils for Food Security and Climate" that was launched at the COP21 of the UNCCD to increase global soil organic matter by 4 per 1,000 (or 0.4%) per year. In order to encourage better management practices among farmers that sequester more carbon, economic incentives could be provided such as direct payments, tax concessions and emission trading tools.

7 Synergies between land degradation neutrality and carbon neutrality

There are clear synergies between LDN and CN as indicated in Figure 1. Synergistic implementation of the neutralities will reduce the total cost and the need for many different expertise. LDN actions will always result in multiple benefits including socioeconomic benefits. Soil organic carbon is an indicator for LDN and therefore many countries have established links between LDN and National Determined Contributions (NDCs). There are several synergistic sectoral impacts. Carbon neutrality will result in positive health outcomes, poverty alleviation, and improvements in national and global security and in the economy.

7.1 Carbon neutrality and health links

There are positive health outcomes from achieving CN. Achieving CN by decarbonizing energy sector, for example, could result in cleaner air which can bring large improvement to the human and ecosystem health. Achieving a net-zero status by the year 2050 will result in a decrease in pollutants like particulate matter (PM), ozone, PM precursors, nitrous oxides (NO_x), sulfur dioxide (SO_2), and other harmful air pollutants (Kerry and McCarthy, 2021).

7.2 Carbon neutrality and poverty link

Many of the climate extreme related costs are mostly borne by the low-income countries and low-income communities (EPA, 2021). Among thermal energy dependent countries, large amounts of NO_x and SO_2 are inevitable. Reductions of such pollutants will result in significant productivity increases of the workforce as a result of health improvements. It has been found that air pollutants can affect educational attainment and thus could result in lowered labor productivity (Zivin and Neidell, 2018). Extreme weather events can also bring disruption of critical health care and such impacts are mostly felt by low-income communities (Mach et al., 2019). Carbon neutrality achieved through LDN provides cost effective solutions for both.

7.3 Synergy between carbon neutrality and economy

Projections from the USA economy shows that avoided damages from fewer deaths, less damage to infrastructure, and fewer lost wages could be $49 billion/year in 2050 if 1.5°C-compatible scenarios have been adopted (Kerry and McCarthy, 2021). For India, net zero will result in net increase in employment opportunities, creating about 15 million jobs beyond a baseline scenario by 2047. Households could save as much as $9.7bn in energy costs by 2060 (ASPI, 2022).

7.4 Synergy between carbon neutrality and security

LDN and CN together could establish national and global security. Continuous disasters drain national financial and infrastructure resources leading to national financial insecurity. More frequent diversion of military assets and personnel to assist and recover the disaster affected regions could result in risks to the national security (Kerry and McCarthy, 2021). In addition, extreme climatic events could bring additional conflicts within the same community and between communities and between nations (Mach et al., 2019).

7.5 Enhancing synergies and minimizing negative feedbacks

In order to enhance the synergies, it is important to adopt actions at different levels. First, it is important to establish linkages within and between biophysical, biogeochemical, and socioeconomic interactions. Second, in order to identify the priority response actions and policy responses, vulnerabilities need to be identified. Thirdly, exchanging the knowledge among stakeholders at various levels and integrating different knowledge systems (e.g., indigenous, citizen science), and co-generating new knowledge, (Raymond et al., 2010; Reed et al., 2011) are essential in fast tracking the response strategies. Finally, innovation is needed to adapt with the changing circumstances (Webb et al., 2017).

When things operate in opposing directions, it implies negative feedback mechanisms. It is therefore important to understand any such negative feedbacks prior to proposing more resilient solutions. Impacts of climate change could lead to desertification and abandonment of lands. Climate change could accelerate land degradation. For example, more frequent droughts, changes in soil properties and vegetation growth can induce land degradation. Therefore, mitigating climate change will inevitably mitigate desertification, too (Reed and Stringer, 2015).

In order to minimize land degradation and climate change negative feedbacks, four core multi-level actions could be adopted. These include, establishing links between land degradation and climate change impacts, identifying most vulnerable systems, improving knowledge and investigate policy options. Reducing emissions from forest degradation and deforestation (REDD+) projects offer a "triple-win," encompassing climate change mitigation, biodiversity conservation, and the well-being of local communities (Siril et al., 2022).

7.6 Synergies among multilateral environmental agreements related to land and climate change

In 2016, the Intergovernmental Panel on Climate Change (IPCC) agreed to create a special report on desertification, land degradation, and climate change, which would complement the Sixth Assessment Report (AR6). Coordination among the UNCCD, UNFCCC, and UN Convention on Biological Diversity (UNCBD) has been improved to identify and harness synergies in response to land degradation and climate change (Chotte et al., 2019). There is further need to integrate chemical related conventions to identify their linkages with land and climate related conventions.

8 Modeling approaches for land degradation neutrality and carbon neutrality

Analysis of a complex problem is easily done with models as they represent the reality in a manageable scale. Understanding the impacts of land degradation and effectiveness of LDN and CN is best done with modeling approaches since they are capable of characterizing impacts that span across much wider spatial and temporal scales. The simplest and the oldest type of models were soil erosion models which provide considerable amount of information toward land degradation from a conventional point of view.

The next type of models has been GIS based maps which are mostly supported by remotely sensed data which provides useful source of information on extents and the severity of land degradation at national and global levels. For example, degradation hotspots among major land cover types were identified using biomass productivity as an indicator of land degradation (Le et al., 2016). This type of information could be verified with ground-based measurements (Anderson and Johnson, 2016).

Recent IPCC reports have illustrated a variety of scenarios, pathways and models that explore future emissions, climate change related impacts and risks, and possible mitigation and adaptation strategies. Most common type of scenarios is Shared Socio-economic Pathways (SSPs) that cover a range of possible future development of anthropogenic drivers of climate change. Under this, the very high GHG emission scenarios (SSP5-8.5) assume CO_2 emissions that roughly double from current levels and the very low scenario (SSP1-1.9) assumes CO_2 emissions declining to net zero around 2050 (IPCC, 2023). In addition, Representative Concentration Pathways (RCPs) were used by the Working Group I and Working Group II of the IPCC to assess regional climate changes, impacts and risks. There have been several models of combining land degradation, LDN and CN scenarios around the world and Table 1 provides a summary.

Modeling approaches provide useful basis toward assessment of degradation and restoration effectiveness. In order to design restoration options, it is required to assess the status of degradation. In order to assess the effectiveness of restoration efforts and level of achievement of LDN and CN, there is the need for accurate measurements. The assessment of degradation is, however, still based on conventional approaches, taking mainly the soil erosion as the main cause of degradation. Soil pollution aspects have rarely been considered in modeling, which poses a greater challenge in restoring majority of landscapes in the coming years.

9 Economics of land degradation neutrality and carbon neutrality

Economics is about allocation of scarce resources with a view to maximize economic efficiency. Environmental and social concerns have become essential components of such analyses lately. Economic efficiency implies maximizing net benefits or minimizing the cost. In the context of LDN or CN, economic analysis becomes an important decision-making tool in allocating scarce resources toward land degradation and carbon emissions while selecting the most efficient option. The essential first step of such an analysis is to identify and to quantify the costs and benefits of each option and then estimate monetary values (Mishra and Rai, 2014). Whenever the full range of monetary estimates are not available, multicriteria analysis could be adopted to overcome issues associated with monetary estimates (Imbrenda et al., 2021). Cost benefit analysis is the most promising approach in evaluating various options applying monetary estimates since it can incorporate the temporal dimensions also to the analysis. Monetary estimates related to LDN and CN could provide a strong basis for implementing economic instruments such as taxes and subsidies.

A variety of estimates available on land degradation is summarized by Nkonya et al. (2016b) using various case studies across several countries. Those studies highlight that preventing land degradation in the first place is much cheaper than letting the damage happen and repairing it later. On average, one USD investment toward restoration of degraded land gives a return of five USD. This stand as a strong incentive for taking action against land degradation (Nkonya et al., 2016d).

10 Challenges

There are several types of challenges in achieving LDN and CN. The complexities associated with understanding the land degradation, uncertainties associated with carbon dynamics and vulnerable socioeconomic situations in developing countries bring the challenges that need to be addressed. First, identification of degradation is a challenge when the complex nature of the current degradation types is considered. For example, although the traditionally considered degradation such as soil erosion are prominent, and can be measured easily in the field context, most of the chemical pollution related degradation are not visible to the naked eye. Specific techniques, assessments and models are required to

TABLE 1 Examples of land degradation and climate change related models.

Source	Model/s	Types of scenarios	Findings
Chen et al. (2023)	Multi-objective land use and land cover (LULC) optimization coupled model with CN objective Integrated valuation of ecosystem services and trade-offs (InVEST) model with IPCC inventory methodology Non-dominated sorting genetic algorithm-II (NSGA-II) and patch-generating land use simulation (PLUS) model	Four LULC scenarios: natural development (ND), low carbon emissions (CE), high carbon storage (CS), and carbon neutrality (CN)	Compared to ND scenario, the LULC patterns within the CE, CS, and CN scenarios exhibit higher LULC values and contribute more to CN
Jones et al. (2023)	Integrated model—FABLE calculator	Four scenarios: status quo, improvements on current trends, land sparing and land sharing.	Land use and agricultural sector are net carbon sinks in both land sparing and land sharing pathways,
Li et al. (2023)	Linear programming model (LPM), Markov, future land use simulation (FLUS), emission coefficients and InVEST	Four scenarios; natural development, spatial planning, low-carbon emission, and high-carbon storage by 2035	Optimized land use patterns in the low-carbon scenarios will result in a greater reduction in carbon emissions and a larger increase in carbon sinks than the spatial planning scenario
Liu et al. (2023)	PLUS	Three land-management scenarios developed and simulated for 2020–2060	Protecting and regenerating forests are more effective than afforestation in lowland tropical areas for storing carbon
Wang et al. (2023)	Land use structure optimization (LUSO)	Carbon neutral scenario and baseline scenario	Under carbon neutral scenario, LULC is more moderate, aggregation degree of the overall landscape spreading degree is increased
Wang et al. (2022)	PLUS	Coupled SSP and RCP scenarios (SSP119, SSP245, and SSP585)	Zone-based management with LULC regulation lead to CN
Udayakumara and Gunawardena (2022)	InVEST sediment retention model; Digital elevation model	Three scenarios: status quo, three land-use intervention scenario with 3 Soil and water conservation (SWC) intervention:	SWC for the watershed reduces the soil erosion rate by 23%. Implementing SWC by farmers requires payment transfers from the fertilizer importing authority.
Williams et al. (2021)	Modeling the entire U.S. energy and industrial system with new analysis tools	Eight deep decarbonization scenarios: expand renewable capacity 3.5-fold, retire coal, maintain existing gas generating capacity, increase electric vehicle and heat pump sales	Actions required in all pathways were similar
Nkonya et al. (2016c)	Uses Landsat data to examine land use change and its impact on sediment loading in hydroelectric power plants	–	Determining the returns to SLM

determine the degradation status and this becomes a challenge in tropical developing countries.

Lack of relevant data could pose another challenge in modeling (Baumgartner and Cherlet, 2016). Correct projections of land degradation toward future requires a large amount of good quality data and these are largely not available or difficult to generate in developing countries. The most appropriate remedial measures are also outcomes of science and technology for the most part and hence expensive. This can be another challenge in identifying and prioritizing suitable remedial measures. Importance of local traditional knowledge can ease the situation to a certain extent, but the complex degradation causes such as chemical pollutants have not yet generated a set of traditional knowledge outcomes and cannot expect those to arise in the near future.

It is important to recognize clearly whether we are moving in the correct pathways in adopting remedial measures since some of remedial measures would involve longer time frames. One should be able to recognize the milestones that ensure the movement in the correct direction. In such contexts, modeling has a role to play and lack of expertise and quality data will pose a challenge for the developing countries.

There is an obligation toward implementation of NDCs under the Paris agreement. However, LDN is not obligatory. Among the NDCs also, there are voluntary components and non-voluntary components which will only be implemented with financial assistance. The larger the non-obligatory component, it is difficult to expect that land and carbon neutralities are priorities of national governments and hence may largely result in non-adoption. This is further exacerbated by the frequent risks associated with many tropical Asian developing countries for example, internal conflicts, financial crises, debt burdens, poor governance (Khan and Al Shoumik, 2022) and disasters which are often the result of climate change (Webb et al., 2017).

One of the biggest challenges is to establish and demonstrate links between LDN and other sectors of the economy. For example, improved LDN and CN may generate forest outputs, agricultural outputs, and better health outcomes as indicated under the Section 7. The main subsequent challenge is to establish quantitative links in physical terms and monetary terms between LDN measures and associated benefits and CN measures and associated benefits. For example, there is a monetary estimate available for social cost of carbon, indicating how much global damage is caused by a ton of carbon emitted to the atmosphere. Similarly, one unit of land degradation reversed could be associated with some x units of agricultural or y units of forest product improvements. Establishing such linkages for different land use and ecosystem types would be a next challenge. Establishing values for other sectors could help the decision making in identifying the best LDN or CN measure that contributes toward other overall of the economy.

11 Discussion

Assessment of degradation of land and proposing the level of intervention needed to restore requires information at various levels. First, the level of degradation and the type and level of restoration need to be assessed. Biophysical assessments are the first level of information which can also be model based. Secondly, it is required to assess whether the society is willing to pay to full cost of restoration by looking at full range of costs and benefits of the operation. Economic analysis is important in this respect. Developing countries in the tropical belt may be restrained by the information and the expertise in making such judgments and therefore LDN may remain as a distant prospect.

Carbon neutrality when achieved together with the LDN may present a win-win case for the poor countries. However, when it is not possible, countries may have to look for financial transfer mechanisms that could provide support for achieving NDCs. This may require a more detailed analysis with emphasis on each and every individual NDC being subjected to an in-depth analysis under the local socioeconomic and technical knowhow conditions.

It is worthwhile understanding the best approaches available both biophysical and policy contexts. Carbon stored by forest tree planting can generate carbon credits which can be sold in the Emissions Trading System (ETS) market (van der Gaast et al., 2018). This is further facilitated by carbon accounting standards that are available and global agreements that are encouraging carbon related payments. However, inclusion of forests in ETS schemes around the world has been complicated due to issues of carbon leakage, permanence and complexity of accounting. International initiatives such as 4 per mille will face challenges during their implementation due to lack of data, limitation of soil sinks and issues related to resource poor farmers and small land holders (Lal, 2016).

Agroforestry involves establishing trees, mostly forest trees in croplands and silvopastoral systems. It enhances carbon sequestration (Zomer et al., 2016) since number of trees in a unit area is higher and it utilizes vertical space. Successful implementation of agroforestry systems toward CN or LDN require careful selection of agroforestry species, monitoring of carbon dynamics and finding suitable financing mechanisms. In the city context, achieving both LDN and CN could be possible with urban forestry and green infrastructure. Maintaining forest cover in urban contexts provides variety of ecosystem services (Khan et al., 2022) including human health benefits.

Complex problems such as climate change and land degradation can be tackled by implementing a full spectrum of complementary policies across multiple sectors rather than relying on any single policy of single sector. Implementing LDN and CN simultaneously would bring multiple benefits since it minimizes the effort and resources required. In the future planning, LDN and CN can be inbuilt into single projects so that it will minimize the efforts of experts, resources and land requirement.

One of the limitations of the study is that majority of modeling studies were available from limited locations. For example, mainland China dominated the modeling studies in the literature. In order to overcome these issues, it is essential that studies are conducted covering a wider geographical context.

12 Summary and conclusion

This paper intended to review the concepts of land degradation, LDN along with CN emphasizing the degradation types, approaches, models available to analyze, synergies, economic aspects and challenges. Different degradation types result in different consequences including short- and long term and sometimes persistent impacts. Understanding degradation as well as monitoring the mitigation requires proper models that are built upon good quality physical data and supported by quantitative economic analysis. Efforts toward LDN and CN may generate multiple benefits across national and global scales. In order to synergize LDN and CN actions with current activities, such benefits need to be quantitatively linked with necessary policy instruments.

The study highlights the need to go beyond the traditional degradation types, the role of different approaches specially in reaching synergies between LDN and CN in order to minimize costs. Such synergies are best brought to light by meeting the challenge of establishing and demonstrating links between LDN and other sectors of the economy in a quantitative way using both physical terms and monetary terms. One unit of land degradation or carbon neutrality could be associated with some x units of another economic sector, be it agriculture, human health, or national security and there is a need to establish such linkages for different land use and ecosystem types in a move toward a carbon neutral and land degradation neutral earth.

Author contributions

MG: Writing – review & editing, Visualization, Investigation, Conceptualization, Writing – original draft. EL: Writing – review & editing, Supervision, Investigation. PG: Writing – review & editing, Supervision, Investigation, Conceptualization.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2024.1398864/full#supplementary-material

SUPPLEMENTARY FIGURE S1
Review protocol.

References

Anderson, W., and Johnson, T. (2016). "Evaluating global land degradation using ground-based measurements and remote sensing" in *Economics of land degradation and improvement–a global assessment for sustainable development*. (eds) E. Nkonya, A. Mirzabaev and J. von Braun (Cham: Springer), 85–116.

Arvaniti, O. S., and Stasinakis, A. S. (2015). Review on the occurrence, fate and removal of perfluorinated compounds during wastewater treatment. *Sci. Total Environ.* 524–525, 81–92. doi: 10.1016/j.scitotenv.2015.04.023

ASPI. (2022). Getting India to net zero. Available at: https://asiasociety.org/sites/default/files/2022-09/ASPI_Getting%20India%20to%20Net%20Zero_Report.pdf

Baumgartner, P., and Cherlet, J. (2016). "Institutional framework of (in) action against land degradation" in *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*. (eds) E. Nkonya, A. Mirzabaev and J. von Braun (Cham: Springer), 33–54.

Beaumelle, L., Tison, L., Eisenhauer, N., Hines, J., Malladi, S., Pelosi, C., et al. (2023). Pesticide effects on soil fauna communities—a meta-analysis. *J. Appl. Ecol.* 60, 1239–1253. doi: 10.1111/1365-2664.14437

Briassoulis, H. (2019). Combating land degradation and desertification: the land-use planning quandary. *Land* 8:27. doi: 10.3390/land8020027

Chae, Y., and An, Y. J. (2018). Current research trends on plastic pollution and ecological impacts on the soil ecosystem: a review. *Environ. Pollut.* 240, 387–395. doi: 10.1016/j.envpol.2018.05.008

Chalise, D., Kumar, L., and Kristiansen, P. (2019). Land degradation by soil erosion in Nepal: a review. *Soil Syst* 3:12. doi: 10.3390/soilsystems3010012

Chan, F. K. S., Chen, J., Li, P., Wang, J., Wang, J., and Zhu, Y. (2023). The cross-boundary of land degradation in Mongolia and China and achieving its neutrality-challenges and opportunities. *Ecol. Indic.* 151:110311. doi: 10.1016/j.ecolind.2023.110311

Chen, L., Msigwa, G., Yang, M., Osman, A. I., Fawzy, S., Rooney, D. W., et al. (2022). Strategies to achieve a carbon neutral society: a review. *Environ. Chem. Lett.* 20, 2277–2310. doi: 10.1007/s10311-022-01435-8

Chen, N., Xin, C., Zhang, B., Xin, S., Tang, D., Chen, H., et al. (2023). Contribution of multi-objective land use optimization to carbon neutrality: a case study of Northwest China. *Ecol. Indic.* 157:111219. doi: 10.1016/j.ecolind.2023.111219

Cheng, H. (2020). Future earth and sustainable developments. *Innovation* 1:100055. doi: 10.1016/j.xinn.2020.100055

Chotte, J. L., Aynekulu, E., Cowie, A., Campbell, E., Vlek, P., Lal, R., et al. (2019). Realising the carbon benefits of sustainable land management practices: guidelines for estimation of soil organic carbon in the context of land degradation neutrality planning and monitoring. A report of the Science-Policy Interface. Bonn, Germany: United Nations Convention to Combat Desertification (UNCCD).

Cowie, A. L., Orr, B. J., Castillo Sanchez, V. M., Chasek, P., Crossman, N. D., Erlewein, A., et al. (2018). Land in balance: the scientific conceptual framework for land degradation neutrality. *Environ. Sci. Pol.* 79, 25–35. doi: 10.1016/j.envsci.2017.10.011

de Morais, V. T. M., Jacovine, L. A. G., Torres, C. M. M. E., Alves, E. B. B. M., de Paiva, H. N., Cruz, R. A. D., et al. (2019). Early assessment of tree species with potential for carbon offset plantations in degraded area from the southeastern Brazil. *Ecol. Indic.* 98, 854–860. doi: 10.1016/j.ecolind.2018.12.004

Deng, X., and Li, Z. (2016). "Economics of land degradation in China" in: *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*.(eds) E. Nkonya, A. Mirzabaev and J. von Braun (Cham: Springer, 385–399.

Dhyani, S., Santhanam, H., Dasgupta, R., Bhaskar, D., Murthy, I. K., and Singh, K. (2023). Exploring synergies between India's climate change and land degradation targets: lessons from the Glasgow climate COP. *Land Degrad. Dev.* 34, 196–206. doi: 10.1002/ldr.4452

EPA (2021). Climate change and social vulnerability in the United States: a focus on six impacts: U.S. Environmental Protection Agency EPA 430-R-21-003. Available at: www.epa.gov/cira/social-vulnerability-report.

Feng, S., Zhao, W., Zhan, T., Yan, Y., and Pereira, P. (2022). Land degradation neutrality: a review of progress and perspectives. *Ecol. Indic.* 144:109530. doi: 10.1016/j.ecolind.2022.109530

Finkbeiner, M., and Bach, V. (2021). Life cycle assessment of decarbonization options—towards scientifically robust carbon neutrality. *Int. J. Life Cycle Assess.* 26, 635–639. doi: 10.1007/s11367-021-01902-4

Fourie, F., Reinecke, S. A., and Reinecke, A. J. (2007). The determination of earthworm species sensitivity differences to cadmium genotoxicity using the comet assay. *Ecotoxicol. Environ. Saf.* 67, 361–368. doi: 10.1016/j.ecoenv.2006.10.005

Gunawardena, U. A. D. P. (2022). "Soil degradation: causes, consequences, and analytical tools" in *Land degradation neutrality: achieving SDG 15 by forest management*. (eds) P. Panwar, G. Shukla, J. A. Bhat and S. Chakravarty (Springer Nature Singapore: Singapore), 155–170.

Hale, R. C., Seeley, M. E., La Guardia, M. J., Mai, L., and Zeng, E. Y. (2020). A global perspective on microplastics. *J. Geophys. Res. Oceans* 125:e2018JC014719. doi: 10.1029/2018JC014719

Hashimi, M. H., Hashimi, R., and Ryan, Q. (2020). Toxic effects of pesticides on humans, plants, animals, pollinators and beneficial organisms. *Asian Plant Res. J.* 5, 37–47. doi: 10.9734/aprj/2020/v5i430114

Hektor, B., Backéus, S., and Andersson, K. (2016). Carbon balance for wood production from sustainably managed forests. *Biomass Bioenergy* 93, 1–5. doi: 10.1016/j.biombioe.2016.05.025

Imbrenda, V., Quaranta, G., Salvia, R., Egidi, G., Salvati, L., Prokopovà, M., et al. (2021). Land degradation and metropolitan expansion in a peri-urban environment. *Geomat. Nat. Haz. Risk* 12, 1797–1818. doi: 10.1080/19475705.2021.1951363

IPCC (2023). "Summary for policymakers" in Climate change 2023: synthesis report. Contribution of working groups I, II and III to the sixth assessment report of the intergovernmental panel on climate change, Core Writing Team. eds. H. Lee and J. Romero (Geneva: IPCC), 1–34.

Jayakody, G. D. C., Weerasinghe, K. G. N. H., Jayasinghe, G. Y., and Halwatura, R. U. (2023). Economical sustainability of vertical greeneries in tropical climate. *Energ. Buildings* 299:113580. doi: 10.1016/j.enbuild.2023.113580

Jones, S. M., Smith, A. C., Leach, N., Henrys, P., Atkinson, P. M., and Harrison, P. A. (2023). Pathways to achieving nature-positive and carbon–neutral land use and food systems in Wales. *Reg. Environ. Chang.* 23:37. doi: 10.1007/s10113-023-02041-2

Kerry, J., and McCarthy, G. (2021). The long-term strategy of the United States, pathways to net-zero greenhouse gas emissions by 2050. Washington, DC: The United States Department of State and the United States executive Office of the President.

Khan, M. Z., and Al Shoumik, B. A. (2022). Land degradation neutrality concerns in Bangladesh. *Soil Secur.* 9:100075. doi: 10.1016/j.soisec.2022.100075

Khan, N., Jhariya, M. K., Raj, A., Bargali, K., Devi, A., and Ghanshyam. (2022). "Urban Forest resources: a strategy for achieving land degradation neutrality" in *Land degradation neutrality: achieving SDG 15 by forest management*. (eds) P. Panwar, G. Shukla, J. A. Bhat and S. Chakravarty (Springer Nature Singapore: Singapore), 363–380.

Kirui, O. K. (2016). "Economics of land degradation and improvement in Tanzania and Malawi" in *Economics of land degradation and improvement–a global assessment for sustainable development*. (eds) E. Nkonya, A. Mirzabaev and J. von Braun (Cham: Springer), 609–649.

Kremen, C., and Miles, A. (2012). Ecosystem services in biologically diversified versus conventional farming systems: benefits, externalities, and trade-offs. *Ecol. Soc.* 17:25. doi: 10.5751/ES-05035-170440

Kriech, A. J., and Osborn, L. V. (2022). Review of the impact of stormwater and leaching from pavements on the environment. *J. Environ. Manag.* 319:115687. doi: 10.1016/j.jenvman.2022.115687

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustain. For.* 7, 5875–5895. doi: 10.3390/su7055875

Lal, R. (2016). Beyond COP 21: potential and challenges of the "4 per thousand" initiative. *J. Soil Water Conserv.* 71, 20A–25A. doi: 10.2489/jswc.71.1.20A

Le, Q. B., Nkonya, E., and Mirzabaev, A. (2016). "Biomass productivity-based mapping of global land degradation hotspots" in *Economics of land degradation and improvement–a global assessment for sustainable development*. (eds) E. Nkonya, A. Mirzabaev and J. von Braun (Cham: Springer), 55.

Li, L., Huang, X., and Yang, H. (2023). Optimizing land use patterns to improve the contribution of land use planning to carbon neutrality target. *Land Use Policy* 135:106959. doi: 10.1016/j.landusepol.2023.106959

Liu, Z., Deng, Z., He, G., Wang, H., Zhang, X., Lin, J., et al. (2022). Challenges and opportunities for carbon neutrality in China. *Nat Rev Earth Environ* 3, 141–155. doi: 10.1038/s43017-021-00244-x

Liu, S., Wang, X., Guo, G., and Yan, Z. (2021). Status and environmental management of soil mercury pollution in China: a review. *J. Environ. Manag.*:277. doi: 10.1016/j.jenvman.2020.111442

Liu, J., Yan, Q., and Zhang, M. (2023). Ecosystem carbon storage considering combined environmental and land-use changes in the future and pathways to carbon neutrality in developed regions. *Sci. Total Environ.* 903:166204. doi: 10.1016/j.scitotenv.2023.166204

Ma, S., Chen, G., Du, E., Tian, D., Xing, A., Shen, H., et al. (2021). Effects of nitrogen addition on microbial residues and their contribution to soil organic carbon in China's forests from tropical to boreal zone. *Environ. Pollut.* 268:115941. doi: 10.1016/j.envpol.2020.115941

Mach, K. J., Kraan, C. M., Adger, W. N., Buhaug, H., Burke, M., Fearon, J. D., et al. (2019). Climate as a risk factor for armed conflict. *Nature* 571, 193–197. doi: 10.1038/s41586-019-1300-6

Maes, J., Barbosa, A., Baranzelli, C., Zulian, G., Batista e Silva, F., Vandecasteele, I., et al. (2015). More green infrastructure is required to maintain ecosystem services under current trends in land-use change in Europe. *Landsc. Ecol.* 30, 517–534. doi: 10.1007/s10980-014-0083-2

Manz, M., Wenzel, K. D., Dietze, U., and Schüürmann, G. (2001). Persistent organic pollutants in agricultural soils of Central Germany. *Sci. Total Environ.* 277, 187–198. doi: 10.1016/S0048-9697(00)00877-9

Minasny, B., Malone, B. P., McBratney, A. B., Angers, D. A., Arrouays, D., Chambers, A., et al. (2017). Soil carbon 4 per mille. *Geoderma* 292, 59–86. doi: 10.1016/j.geoderma.2017.01.002

Mishra, P. K., and Rai, S. C. (2014). A cost–benefit analysis of indigenous soil and water conservation measures in Sikkim Himalaya, India. *Mount. Res. Dev.* 34, 27–35. doi: 10.1659/MRD-JOURNAL-D-12-00013.1

Morgan, J. E., and Morgan, A. J. (1992). Heavy metal concentrations in the tissues, ingesta and faeces of ecophysiologically different earthworm species. *Soil Biol. Biochem.* 24, 1691–1697. doi: 10.1016/0038-0717(92)90171-S

Mythili, G., and Goedecke, J. (2016). "Economics of land degradation in India" in *Economics of land degradation and improvement–a global assessment for sustainable development*. (eds) E. Nkonya, A. Mirzabaev and J. von Braun 431–469.

Nkonya, E., Anderson, W., Kato, E., Koo, J., Mirzabaev, A., von Braun, J., et al. (2016a). "Global cost of land degradation" in *Economics of land degradation and improvement–A global assessment for sustainable development*. (eds) E. Nkonya, A. Mirzabaev and J. von Braun (Cham: Springer), 117–165.

Nkonya, E., Mirzabaev, A., and Von Braun, J. (2016b). *Economics of land degradation and improvement–a global assessment for sustainable development*. (Cham: Springer Nature).

Nkonya, E., Mirzabaev, A., and von Braun, J. (2016d). "Economics of land degradation and improvement: an introduction and overview" in *Economics of land degradation and improvement–a global assessment for sustainable development*. (eds) E. Nkonya, A. Mirzabaev and J. von Braun (Cham: Springer), 1–14.

Nkonya, E., Srinivasan, R., Anderson, W., and Kato, E. (2016c). "Economics of land degradation and improvement in Bhutan" in *Economics of land degradation and improvement–a global assessment for sustainable development*. (eds) E. Nkonya, A. Mirzabaev and J. von Braun (Cham: Springer), 327–383.

Prăvălie, R. (2021). Exploring the multiple land degradation pathways across the planet. *Earth Sci. Rev.* 220:103689. doi: 10.1016/j.earscirev.2021.103689

Raymond, C. M., Fazey, I., Reed, M. S., Stringer, L. C., Robinson, G. M., and Evely, A. C. (2010). Integrating local and scientific knowledge for environmental management. *J. Environ. Manag.* 91, 1766–1777. doi: 10.1016/j.jenvman.2010.03.023

Reed, M. S., Buenemann, M., Atlhopheng, J., Akhtar-Schuster, M., Bachmann, F., Bastin, G., et al. (2011). Cross-scale monitoring and assessment of land degradation and sustainable land management: a methodological framework for knowledge management. *Land Degrad. Dev.* 22, 261–271. doi: 10.1002/ldr.1087

Reed, M., and Stringer, L. C. (2015). Climate change and desertification: anticipating, assessing & adapting to future change in drylands. Montpellier: Agropolis International.

Rillig, M. C. (2012). Microplastic in terrestrial ecosystems and the soil? *Environ. Sci. Technol.* 46, 6453–6454. doi: 10.1021/es302011r

Scopetani, C., Chelazzi, D., Cincinelli, A., Martellini, T., Leiniö, V., and Pellinen, J. (2022). Hazardous contaminants in plastics contained in compost and agricultural soil. *Chemosphere* 293:133645. doi: 10.1016/j.chemosphere.2022.133645

Serrano-Ruiz, H., Martin-Closas, L., and Pelacho, A. M. (2021). Biodegradable plastic mulches: impact on the agricultural biotic environment. *Sci. Total Environ.* 750:141228. doi: 10.1016/j.scitotenv.2020.141228

Shukla, G., Rai, P., Manohar, K. A., and Chakravarty, S. (2020). Quantification of diversity, biomass and carbon storage of climber and liana community in a foothill forest of Indian eastern Himalayas. *Acta Ecol. Sin.* 40, 478–482. doi: 10.1016/j.chnaes.2020.09.009

Siril, S., Singh, M., Shahina, N. N., Bhat, J. A., Shukla, G., Panwar, P., et al. (2022). "Role of REDD+ in reducing land degradation and achieving SDGs" in *Land degradation neutrality: achieving SDG 15 by Forest management*. (eds) P. Panwar, G. Shukla, J. A. Bhat and S. Chakravarty (Springer Nature Singapore: Singapore), 303–313.

Slipenchuk, M., Kirillov, S., Vorobievskaya, E., and Sedova, N. (2019). "Anthropogenic pollution of the southern part of the khibiny mountain massif and foothills" in *IOP Conference Series: Earth and Environmental Science*. 302:012024. doi: 10.1088/1755-1315/302/1/012024

Tang, F. H., Lenzen, M., McBratney, A., and Maggi, F. (2021). Risk of pesticide pollution at the global scale. *Nat. Geosci.* 14, 206–210. doi: 10.1038/s41561-021-00712-5

Udayakumara, E. P. N., and Gunawardena, P. (2022). Modelling soil erosion and hydropower linkages of Rantambe reservoir, Sri Lanka: towards payments for ecosystem services. *Model. Earth Syst. Environ.* 8, 1617–1634. doi: 10.1007/s40808-021-01169-6

UN. (2015). *Transforming our world: the 2030 agenda for sustainable development*. A/RES/70/1. United Nations.

UNCCD (1994). United Nations convention to combat desertification in those countries experiencing serious drought and/or desertification. Paris: Particularly in Africa Available at: https://catalogue.unccd.int/936_UNCCD_Convention_ENG.pdf.

UNCCD (Ed.) (2017). United Nations convention to combat desertification – Global land outlook. *1st* Edn. Bonn: UNCCD Secretariat.

UNCCD. (2024). Land degradation neutrality. Available at: https://www.unccd.int/land-and-life/land-degradation-neutrality/overview (Accessed March 9, 2024).

UNEP (2016). Enhancing cooperation among the seven biodiversity related agreements and conventions at the national level using national biodiversity strategies and action plans. Nairobi: United Nations environment Programme (UNEP).

UNFCCC. (2021). Climate neutral now: guidelines for participation. Available at: https://unfccc.int/sites/default/files/resource/Guidelines%20CNN%20version%201.4.pdf

UNFCCC. (2024). What is the United Nations framework convention on climate change? Available at: https://unfccc.int/process-and-meetings/what-is-the-united-nations-framework-convention-on-climate-change (Accessed February 24, 2024).

Uwizeyimana, H., Wang, M., Chen, W., and Khan, K. (2017). The eco-toxic effects of pesticide and heavy metal mixtures towards earthworms in soil. *Environ. Toxicol. Pharmacol.* 55, 20–29. doi: 10.1016/j.etap.2017.08.001

van der Gaast, W., Sikkema, R., and Vohrer, M. (2018). The contribution of forest carbon credit projects to addressing the climate change challenge. *Clim. Pol.* 18, 42–48. doi: 10.1080/14693062.2016.1242056

Wang, K., Li, X., Lyu, X., Dang, D., Dou, H., Li, M., et al. (2022). Optimizing the land use and land cover pattern to increase its contribution to carbon neutrality. *Remote Sens.* 14:4751. doi: 10.3390/rs14194751

Wang, Z., Zhang, F., Liu, S., and Xu, D. (2023). Land use structure optimization and ecological benefit evaluation in Chengdu-Chongqing urban agglomeration based on carbon neutrality. *Land* 12:1016. doi: 10.3390/land12051016

Webb, N. P., Marshall, N. A., Stringer, L. C., Reed, M. S., Chappell, A., and Herrick, J. E. (2017). Land degradation and climate change: building climate resilience in agriculture. *Front. Ecol. Environ.* 15, 450–459. doi: 10.1002/fee.1530

Weber, R., Watson, A., Forter, M., and Oliaei, F. (2011). Persistent organic pollutants and landfills-a review of past experiences and future challenges. *Waste Manag. Res.* 29, 107–121. doi: 10.1177/0734242X10390730

Williams, J. H., Jones, R. A., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., et al. (2021). Carbon-neutral pathways for the United States. *AGU Adv.* 2:e2020AV000284. doi: 10.1029/2020AV000284

Wu, X., Tian, Z., and Guo, J. (2022). A review of the theoretical research and practical progress of carbon neutrality. *Sustain. Operat. Comput.* 3, 54–66. doi: 10.1016/j.susoc.2021.10.001

Yang, X., Zhang, X., Shu, X., Gong, J., Yang, J., Li, B., et al. (2023). The effects of polyethylene microplastics on the growth, reproduction, metabolic enzymes, and metabolomics of earthworms *Eisenia fetida*. *Ecotoxicol. Environ. Saf.* 263:115390. doi: 10.1016/j.ecoenv.2023.115390

Zivin, J. G., and Neidell, M. (2018). Air pollution's hidden impacts. *Science* 359, 39–40. doi: 10.1126/science.aap7711

Zomer, R. J., Neufeldt, H., Xu, J., Ahrends, A., Bossio, D., Trabucco, A., et al. (2016). Global tree cover and biomass carbon on agricultural land: the contribution of agroforestry to global and national carbon budgets. *Sci. Rep.* 6:29987. doi: 10.1038/srep29987