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REVIEW ARTICLE

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Climate change-triggered land degradation and planetary health: A review

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Abstract
Land is a vital natural resource for human socio-ecological wellbeing. Around the world, land is being degraded due to various natural and anthropogenic factors such as flooding, wind erosion, agriculture and human settlement, and anthropogenic climate change. While significant research has been conducted on the separate dyads of: (1) anthropogenic climate change and land degradation and (2) land degradation and health, limited consideration has been given to the cause-and-effect relationships between anthropogenic climate change-triggered land degradation and planetary health consequences. Using a systematic literature review and the driving force, pressure, state, exposure, effect (DPSEE) framework, this study synthesizes the complex causal relationships of anthropogenic climate change-triggered land degradation and its planetary health consequences. Our findings demonstrate that anthropogenic climate change has induced and accelerated natural and anthropogenic land degradation through an array of pathways, resulting in planetary health consequences that can be grouped into six categories: (1) food and nutritional insecurity, (2) communicable and noncommunicable diseases, (3) livelihood insecurity, (4) physical and mental health, (5) health hazards related to extreme weather events, and (6) migration and conflict. Interlinkages exist between these six planetary health impact categories, adding to the complexity of the causal pathways. These collective impacts are hampering the realization of the UN Sustainable Development Goals around the world. The findings of this study and our DPSEE framework can help policymakers identify and integrate actions to better manage the planetary health impacts of climate change-induced land degradation.

KEYWORDS
climate change, DPSEE (drivers forces, pressure, state, exposure, effect) model, land degradation, planetary health

1 | INTRODUCTION

Until recently, science and policy perspectives on the public health of human populations have not necessarily considered natural ecosystems (Horton et al., 2014). These systems are now under significant threat in the Anthropocene epoch (Lewis & Maslin, 2015), and in some cases are leading to accelerated species extinction (Thomas et al., 2004), nature loss and degradation of natural systems (WHO, 2015), and as a consequence, pose serious threats to human health and wellbeing (Díaz et al., 2015; Whitmee et al., 2015). Climate change is a key driver of changing Earth systems and has been declared the greatest threat to global human health in the twenty-first century (Whitmee et al., 2015). The Intergovernmental Panel on Climate Change (IPCC) warned that the world's natural and human systems will face severe challenges if greenhouse gas emissions continue to rise (IPCC, 2018). The impact of climate change has already been significant enough to endanger human health both directly and indirectly through the alteration of the Earth's interrelated systems (Watts et al., 2015).

The link between human health and the planet's natural systems is core to the concept of *planetary health*, which is now an emergent and powerful framework for redefining human clinical public health in relation to earth's natural systems (Lade et al., 2020; Myers et al., 2013). First declared as a Manifesto in the 2015 *Rockefeller Foundation–Lancet Commission on Planetary Health*, planetary health is defined as "...the achievement of the highest attainable standard of (human) health, wellbeing, and equity worldwide through judicious attention to the human systems—political, economic, and social—that shape the future of humanity and the Earth's natural systems that define the safe environmental limits within which humanity can flourish" (Whitmee et al., 2015). As described by *the Lancet* medical journal Editor, "...planetary health is a new science that is only beginning to draw the coordinates of its interests and concerns" (Horton & Lo, 2015). In this paper, we focus on land degradation and implications for planetary health.

Land degradation threatens the wellbeing of 3.2 billion people worldwide, with approximately 75% of Earth's land area degraded (IPBES, 2018). Global land degradation is happening as a consequence of various natural and anthropogenic mechanisms including flood, wind erosion, salinization, agriculture and human settlement, mining, deforestation, fire, and anthropogenic climate change (IPBES, 2018; IPCC, 2019; MEA, 2005). The direct and indirect causes of land degradation and their human socio-ecological impacts are well documented (IPBES, 2018; IPCC, 2019). Land degradation is responsible for the loss of biodiversity and biological productivity and causes imbalances in human socio-ecological integrity (Byrnes et al., 2018; IPBES, 2018; IPCC, 2019; Kidane et al., 2019; MEA, 2005; Mirzabaev et al., 2016; Nunes et al., 2020; Santini et al., 2020).

Land degradation and climate change each contribute to the other's acceleration. As climate change intensifies natural and anthropogenic land degradation, soil-based carbon released from degraded land to the atmosphere and reductions in carbon sequestration contributes to accelerate climate change (IPBES, 2018; IPCC, 2019; IUCN, 2015). Land degradation has associated human health risks and is directly or indirectly impacting planetary health through multiple complex pathways. Limited consideration has been given in the literature to the cause-and-effect relationship of anthropogenic climate change and land degradation and the related planetary health effects. To understand these relationships, we ask two questions: (1) 'How is climate change causing land degradation?' and (2) 'What potential planetary health consequences are associated with land degradation?' This study answers with an identification and synthesis of the complex causal relationships of anthropogenic climate change induced land degradation and its planetary health consequences. By integrating information available currently siloed in two dyads—land degradation and climate change, and land degradation and health—this paper provides a holistic yet focussed understanding of the potential threats to human health and well-being by climate change—induced land degradation.

2 | METHODOLOGY

We developed (1) a dataset using a systematic literature review and (2) a driving force, pressure, state, exposure, effect (DPSEE) framework using the collected data to identify how climate change has contributed to land degradation and the resulting human health impacts.

2.1 | Systematic literature review to create a database

The PRISMA strategic process (Moher et al., 2009) was deployed for the systematic literature review, using its four steps: identification, screening, eligibility, and Included (see Figure 1). In the Identification step, several preliminary pilot searches were conducted to test the search strategy and keywords. Then, Web of Science and Google databases were extensively searched using a combination of keywords (i.e., land, soil, land degradation, soil degradation, climate change, global warming, health, human health, and planetary health) for peer-reviewed articles, reviews, and gray literature on (1) the nexus of land degradation-climate change-health, (2) land degradation and climate change, and (3) land degradation and health. No date and language restrictions were imposed, and all studies in the search results were in English.

In the screening step, a protocol was developed for selecting the literature that was relevant to the goals of this paper. Studies that only included the driving forces of land degradation but not the processes were excluded. Inclusion and exclusion criteria were strictly applied, excluding papers where there was a lack of information on land degradation processes related to the impact of climate change and links with human health impacts.

In the eligibility step, 38 articles, reviews, and book chapters that focused on (1) the processes or direct mechanisms of land degradation in the context of climate change and (2) the pathways through which these degraded processes may impact planetary health were identified as eligible. A common observation throughout the literature review was a lack of specificity about the health impacts of land degradation and climate change, which required the researchers to use a snowball method to seek out 56 additional articles, reports, and commentaries outside of the 38 articles to develop the causal pathways in the model.

In the Included step, 94 documents comprising of articles, book chapters, reviews, reports, and commentaries were identified for thorough review.

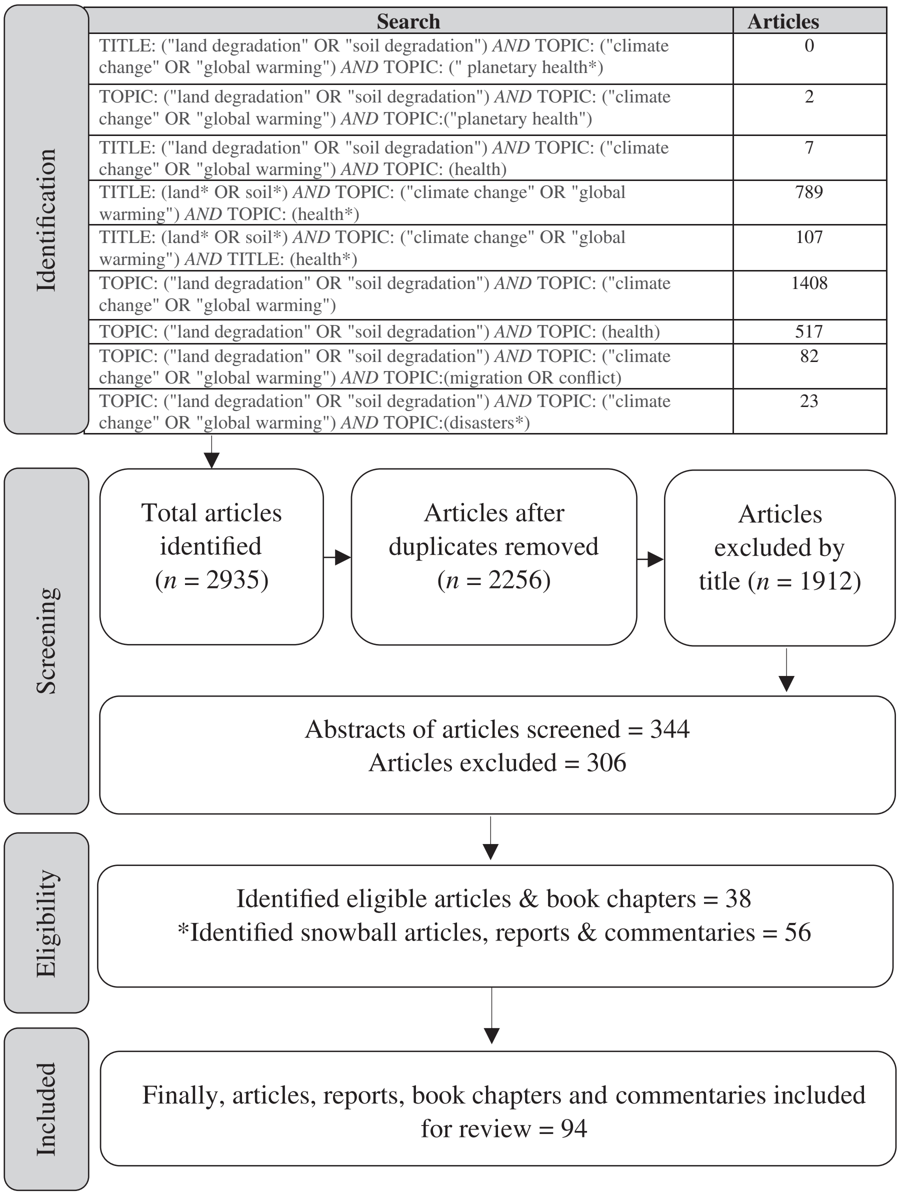

FIGURE 1 Steps in the PRISMA systematic literature for creating the database. Asterisk indicates snowball method from other reviews and articles

2.2 | DPSEE framework

To develop the DPSEE framework, data reflected in these 94 articles related to climate change-driven land degradation, related pressures, state, exposure pathways, and associated health impacts were inserted in a MS Excel spreadsheet based on predetermined codes that were aligned with the study's objectives. The title, abstract, keywords, authors' names, journal name, and year of publication of the selected 94 articles were inserted in the same spreadsheet.

Three key international reports were used for guidance to find and integrate data to develop DPSEE: (1) *Summary for Policymakers: Climate Change and Land: An IPCC Special Report on Climate Change, Desertification, Land Degradation* (IPCC, 2019), (2) *The Assessment Report on Land Degradation and Restoration* (IPBES, 2018), and (3) *Land Degradation Assessment in Drylands* (FAO, 2011).

Using the spreadsheet data, the DPSEE framework was constructed as illustrated in Figure 2. The DPSEE framework is modified from the DPSEEA framework of von Schirnding (2002). DPSEEA presents the components in a linear fashion in order to represent the connections between factors affecting health and the environment more clearly (von Schirnding, 2002). 'Action' (A), which is included in the DPSEEA framework, is out of the scope of this study and therefore is not addressed.

3 | RESULTS

This section presents the results of a meta-synthesis of the data to identify and understand how climate change triggers further land degradation and the resulting consequences on planetary health.

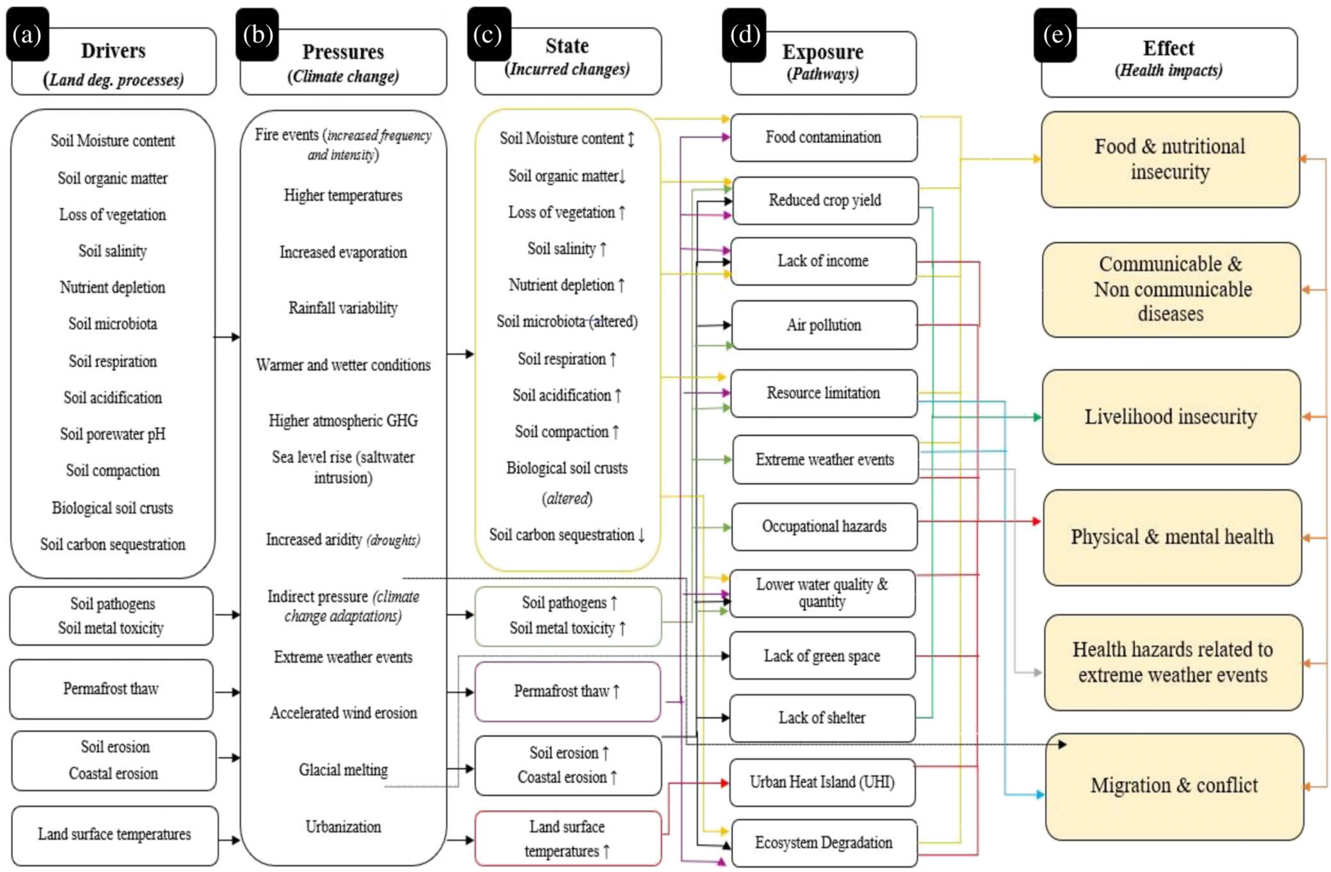

FIGURE 2 The driving force, pressure, state, exposure, effect (DPSEE) framework of the connectivity between land degradation processes and planetary health consequences in the context of climate change. In the figure '↑' indicates increase, '↓' indicates decrease and '↕' indicates increase or decrease of the state. The colored arrows are for visual enhancement purposes only. Drivers in the diagram represent the mechanisms/processes that drive land degradation; pressures represent climate change-induced pressures; state represents how the drivers (i.e., land degradation processes) change as a result of climate change; exposure represents exposure pathways for human beings; and effects represent the resulting planetary health impacts [Colour figure can be viewed at wileyonlinelibrary.com]

3.1 | Climate change-triggered land degradation

The DPSEE model in Figure 2 shows the pathways to the planetary health consequences of land degradation in the context of climate change. Globally, the physical, chemical, and biological properties of soil [see Part (a) of Figure 2] are continuously being modified in response to natural and anthropogenic activities. Many of the changes are caused by human activities, which frequently lead to the degradation of soil. As shown in Part (b) of Figure 2, climate change is triggering further land degradation through higher temperatures, higher water evaporation rates, heavy rainfall, drought, increased salinity, acidification, frequent floods, storms, and glacier retreat (IPBES, 2018; IPCC, 2019). These pressures create a state [see Part (c) of Figure 2] that affects various aspects of the human socio-ecological systems on which planetary health depends and thus affect human health in the ways as shown in Part (d) of Figure 2. For example, decreased soil moisture results in food contamination and reduced crop yields, leading to infectious diseases, and malnutrition among humans (Lal, 2009).

Through the literature reviews, six sub-categories of planetary health impacts were identified [as listed in Part (e) of Figure 2] that can be linked to land degradation processes directly or indirectly. Each subcategory can affect at least one other category through these complex interrelationships. Among these effects, food insecurity was the dominant concern in the articles reviewed.

3.2 | Planetary health consequences

The planetary health consequences of land degradation augmented by climate change have been identified and grouped in six categories which are discussed below.

3.2.1 | Food and nutritional insecurity

Over 95% of humans' food comes directly or indirectly from land (FAO, 2015). Land degradation resulting from climate change can lead to food and nutritional insecurity in several ways. Climate change exacerbates land degradation by influencing several of the processes that alter soil quality and quantity in a way that hampers agricultural yield. For example, climate change accelerates topsoil loss by increased erosion (Li et al., 2020). Topsoil is endangered by both wind and water erosion (Li et al., 2020; Sulaeman & Westhoff, 2020). Climate change-related high temperature and enhanced speed of wind dry the soil and exacerbate wind erosion (Li et al., 2020). Erratic and short-burst heavy rainfall and pluvial, fluvial, and ocean surge flooding induced by climate change increases erosion by water (Borrelli et al., 2020), which degrades land by removing topsoil. Soil formation is a very slow process; typically, only 2 or 3 cm of new soil are created over a 100-year period (USDA, 2020) by weathering in situ. This or an even deeper layer of valuable topsoil can be removed during only one severe rainfall or wind event. Topsoil contains essential nutrients for crops, and the loss of this soil decreases soil fertility, which can negatively affect crop yields (Sulaeman & Westhoff, 2020).

Climate change-induced intensified rainfall and increased total rainfall events increase leaching rates in soils that are well drained and have high infiltration rates. Increased leaching hampers matter decomposition in soils (Brinkman & Sombroek, 1996), and leaching of nutrients reduces crop yield.

Climate change affects soil moisture through rising temperatures and extreme events such as droughts (Green et al., 2019). In their study Huang & Shao (2019) describe that low moisture content in the soil of semi-arid and arid ecosystems makes them especially vulnerable when ambient temperatures are higher, adding to the challenge of providing sufficient moisture for crop growth. In extreme cases, loss of soil moisture associated with rising temperatures is leading to increased desertification in areas like the Sahel in Africa (IPCC, 2019). Continuing warming and reduced precipitation strongly impact desert soil water balance by altering the hydrological performances of biological soil crusts (Li et al., 2018). Soil moisture is critical in maintaining land-surface-plant-atmosphere interactions (Huang & Shao, 2019) by influencing a number of other soil functions like microbial respiration (Manzoni et al., 2012), carbon sink capacities (Alhassan et al., 2018; Fierer & Schimel, 2003), nutrient (carbon and nitrogen), cycling (Fierer & Schimel, 2002), run-off generation (Castillo et al., 2003), dust outbreaks (Fécan et al., 1998), soil-borne pathogens (Avila et al., 2019), and crop productivity (Denmead & Shaw, 1960). Soil moisture is crucial for sustainable improvement of food production; without soil moisture crop yield will decline (Shaxson & Barber, 2003). Climate change can alter soil porosity through compaction, hardening, sealing, and slaking (breakdown of soil after wetting). It can also lead to the loss of soil organisms like earthworms (Chan, 2011), and shortened recovery times due to longer frost-free periods (Puhlick & Fernandez, 2020).

Increased annual temperatures also accelerate the rate of decomposition of organic matter in the soil, which in turn damages the capacity of soil water storage, balance of soil nutrients, and aggregate stability and alters the microbial population in the soil. All these are essential to maintaining the soil's structure, fertility, productivity, resilience, adaptability, and sustainability or in other words, the overall soil health (Chan, 2011; Singh et al., 2011). Weak soil health makes it more susceptible to diseases, invasive species such as weed, and increases pestilence to crops (Larkin, 2015). In general, sound soil health is a prerequisite to ensure agricultural productivity as well as providing other ecosystem services (Brevik & Burgess, 2014; Chan, 2011; FAO, 2015; Larkin, 2015; Singh et al., 2011).

There are ways in which the impact of climate change on soil erosion can be reduced; the most important of these is by increasing soil carbon content. Soil carbon supports aggregate formation and stability through elevated production of the fungal glycoprotein glomalin in soil. Soil aggregation can prevent soil loss through water and wind erosion and enhance the chemical, biological, and agricultural properties of soil (Rillig et al., 1999). Aggregation also produces an appropriate soil structure that encourages good rates of water infiltration (Blevins & Frye, 1993), which are vital for soil functions and ecosystem (Li et al., 2017) as well as crop production.

As sea levels rise due to the thermal expansion of ocean water and the melting of glaciers and polar ice, (Zhang et al., 2013) increasing areas of coastal land will be water inundated (Kirezci et al., 2020). As a result, a vast portion of coastal land will be lost, and salinization may make adjacent land unusable for crop production. Aside from the actual loss of land, saltwater intrusion caused by rising sea levels and severe drought events causes elevated soil porewater salinity in agricultural lands and in tidal freshwater forested wetlands often exceeding plant salinity thresholds (2 psu). This has the potential to disrupt essential ecosystem services including, but not limited to, carbon sequestration, water quality improvement, and habitat for critical wildlife species (Wang et al., 2020). Salinity is one of the most influential limiting factors of plant growth (Shrivastava & Kumar, 2015). Increasing salinity lowers the productivity of soils, sometimes preventing any significant growth or in some cases making crop growth impossible.

There are other salinity issues that are not connected with ocean incursion. Higher temperatures cause more evapotranspiration and increase the need for irrigation in some areas. Evaporation of irrigation water often creates high salt content in the surface soils and ultimately makes the land unsuitable for crop cultivation (Nadeem & Ahmad, 2019; Zurqani et al., 2019). In such cases, climate change-induced reduced productivity and desertification has been found to exacerbate food insecurity, especially in rural areas with disadvantaged communities that are dependent on land for food and livelihoods based on agricultural and pastoral activities (Jaramillo-Mejía & Chernichovsky, 2019). Climate change is making arid, semi-arid, and coastal areas especially vulnerable to soil salinity (Corwin, 2021). Around the world, increased salinity in the soil due to climate change will hamper agricultural yield (Chen & Mueller, 2018a, 2018b).

In some locations, climate change exacerbates desertification through changes in spatial and temporal temperatures, rainfall, solar radiation, and winds (WMO, 2007). Desertification degrades land by turning fertile land into desert areas (WHO, 2020). The best-known example of desertification is the Sahel region of Africa, which is rapidly losing land suitable for crop production (Mbow et al., 2017).

3.2.2 | Communicable and noncommunicable diseases

Climate change-related land use and land cover change will trigger land degradation by modifying the condition, structure, distribution, and composition of natural and human-managed ecosystems (i.e., forest, grassland, tundra, prairie, and agricultural land; Grimm et al., 2013). These modifications may increase the prevalence of diseases since modifying ecosystems enables the spread of pathogens to new ecological niches with negative effects on human health (Taylor et al., 2001). Land transformation (such as from forest to agricultural land), forest fragmentation, and increased encroachment of wildlife habitat can increase the incidence of vector-borne diseases like malaria (Yasuoka & Levins, 2007) and zoonotic diseases like Ebola virus, Coronavirus disease 2019 (COVID-19) and severe acute respiratory syndrome (SARS) (Rulli et al., 2021). Myers et al. (2013) found that land degradation affects human health by changing disease ecologies. Collins (2001) and observed that high vulnerability to infectious diseases in many parts of the world often co-exists with land degradation (Collins, 2001).

Climate change has increased the number of plant pathogens like soil-borne fungi (e.g., *A. alternata*, *Fusarium oxysporum*, and *Aspergillus flavus*) in degraded land. Global field surveys show a worldwide increase in soil-borne fungal plant pathogens in warmer temperature scenarios, especially in drylands and tropical ecosystems (Delgado-Baquerizo et al., 2020; Fouché et al., 2020). These pathogens pose serious threats to food security, timber supply, and livestock, animal, and human health. In addition, deteriorated land such as that under climate change-related drought is subject to the effect of Aflatoxins (*Aspergillus* spp., Fouché et al., 2020), which can cause cytotoxic effects on human blood cells, autoimmune diseases, cancer, and birth defects in children (WHO, 2018). Aflatoxins also can increase under climate change conditions (Paterson & Lima, 2010).

A study of a surge in coccidioidomycosis (valley fever) caused by the *Coccidioides immitis* soil fungus found that exposure to the dust carrying the pathogen could be linked to occupational as well as environmental exposure, with a potential for the latter to increase with climate-related events like drought and fire in endemic areas (Pearson et al., 2019). Opportunistic human pathogens have been detected in soil-borne pathogenic bacteria, resulting in gastrointestinal diseases, respiratory infections, and skin and wound infections; these are made worse by antimicrobial resistance triggered by increased soil pollution that limits the treatability of infections (Ferraresso et al., 2020).

In addition, climate change-induced extreme weather events that result in frequent changes between freezing and thawing may affect the equilibrium between adsorbed and non-adsorbed pesticides. The loss of this equilibrium leads to enhanced leaching, and runoff, with negative consequences for human health through contaminated groundwater and surface water (Saha et al., 2019). Thawing permafrost in tundra areas may release toxic, carcinogenic, and mutagenic heavy metals from previously frozen soils, contaminating food and water resources through freshwater, plants, and wildlife (Perryman et al., 2020).

Prolonged drought is the source of sand and dust storms (SDS) and can amplify wildfires. Climate change triggers the occurrence of more extreme wind events that move to drier climates and act as an important driving force of future wind erosion and SDS.

Increased aridification or desertification caused by prolonged droughts and extreme heat events can amplify the effects of wind erosion, contributing to aerosol and dust emissions with direct health consequences (Peterman & Ferschweiler, 2016). Desertification can have severe and multiple social and economic consequences (Whitford & Duval, 2020) which can culminate in serious health impacts through nonlinear routes. For example, a study conducted in Colombia found that the infant mortality rate due to malnutrition was 2.25-times higher in rural areas with high desertification (more 50% of the area is desert). It must be noted here that ecosystem degradation was not the sole causal factor, and anthropogenic factors like illegal mining activities and monopolization of water resources also play a significant role and must not be overlooked (Jaramillo-Mejía & Chernichovsky, 2019).

Increased aridity is therefore of considerable concern among nations and the international community for its harmful effects on human health. It may lead to malnutrition by damaging plants, agriculture, and livestock and cause acute and chronic respiratory problems by carrying pathogens and harmful substances (UNEP et al., 2016).

3.2.3 | Livelihoods insecurity

Land degradation sparked by climate change can cause increasing livelihood insecurity and loss of economic opportunity (Collins, 2001; Gitz et al., 2016; IPCC, 2019). Land, ecosystem services, and livelihoods are interlinked with climate change through complex pathways that are more prominent in natural resource-dependent communities (King et al., 2019). A survey in Zimbabwe showed how negative transformation of the landscape by climate change over the course of 20 years has forced people relying on rainfed agriculture for their livelihoods to seek alternative sources of food through wildlife poaching and harvesting edible shrubs (Musakwa et al., 2020). As noted above, climate change-induced increase of aflatoxin contamination can negatively affect clinical public health, crop yield, and food security, making it a significant threat to the livelihoods of the farmers. Around the world crop loss due to aflatoxin mean that farmers also face serious economic implications. Globally aflatoxin caused crop loss can have serious economic implications as it can destroy as large as 25% of the world's food crops (WHO, 2018).

Changes in temperature, moisture, and rainfall not only affect plant physiology but also increase the prevalence of plant pathogens and pests that also can potentially reduce crop productivity (Avila et al., 2019; Curlevski et al., 2014; Döring et al., 2020; Moretti et al., 2019) and lead to livelihood, food, and nutritional insecurity. Biogeochemical changes in soil and water in coastal agroecosystems due to climate change may cause nutrient export (dissolved inorganic N, soluble reactive P) downstream from these coastal farmlands, leading to nutrient pollution issues in watersheds (Weissman & Tully, 2020) and making agriculture and livelihoods vulnerable. Climate change will exacerbate land degradation processes through sea level rise, more frequent and severe floods and droughts, and intensified cyclones, which will cause loss of land that supports livelihoods and new income opportunities for millions of people around the world (Gitz et al., 2016; IPCC, 2019). Livelihood insecurity can also impact human health as a result of reduced health care affordability (Obrist et al., 2007).

3.2.4 | Physical and mental health

Climate change-induced land degradation alters the nexus of food, energy, and water in ecosystems (Mbow et al., 2019), often making them less supportive of livelihoods (Mbow et al., 2019; Olsson et al., 2019). Limited scope of livelihoods can lead to many physical and mental health pressures (Hayes et al., 2018). Degraded land promotes poor living conditions due to water scarcity, soil erosion, and flood risk (Munoth & Goyal, 2020). Poor living conditions can cause many problems for mental and physical health. Multiple forms of psychological pathology like "...anxiety, distress, depression, post-traumatic stress disorder, and suicide" have been associated with acute events like storms, and chronic climate disruptions such as rising temperatures and changes to landscape (Manning & Clayton, 2018, p. 217). Land degradation can also limit presence of healthy green and natural environments and increase pollution, both of which can threaten mental and physical wellbeing (Barton, 2009).

3.2.5 | Health hazards related to extreme weather events

Climate change-induced land degradation and its associated loss of ecosystem services can trigger more frequent and more intense natural hazards such as flooding, droughts, and wildfires (FAO, 2011; MEA, 2005). For instance, when climate change increases the soil and water salinity of coastal zones, degraded coastal land provides diminished functionality as when there is the destruction of mangrove forests. The damage of mangrove forests due to salinity and warmer sea temperatures increases the impacts and risk of storm surges and their related health hazards such as loss of safe living space for an extended period, drinking water scarcity, injury, and drowning in countries such as the Philippines, Jamaica, Myanmar, and Bangladesh (UNEP, 2014). Such health hazards can be caused by the destruction of infrastructure and livelihood sources like water, sanitation, and hygiene facilities, roads, homes, crops, and livestock by cyclones and hurricanes (Rafa et al., 2021; Shultz et al., 2020). In inland contexts, unsustainable land management practices combined with climate change-induced deforestation on slopes make these areas especially vulnerable to landslide-related health hazards (FAO, 2015; UNISDR & ECHO, 2011).

3.2.6 | Migration and conflict

Olsson et al. (2019) describe that when degraded land becomes less productive through various mechanisms, this can become a trigger for population dislocation leading sometimes to migration and conflict (Warner et al., 2010). Seawater flooding and soil salinity caused by sea-level rise have been found to have direct impacts on internal and external migration in Bangladesh (Chen & Mueller, 2018a, 2018b). As displaced populations from low-lying areas migrate to higher ground to escape recurring disasters or degraded land, they face serious health problems in connection with the various physiological and psychological stresses of the migration process (Sharma, 2012).

Changes or reductions in land use can lead to conflicts due to poor resource access or scarcity. Climate change interacts directly (droughts) and indirectly (climate-related mitigation and adaptation measures) with land scarcity, and can generate conflicts between communities, governments, and private institutions (Froese & Schilling, 2019; Hunsberger et al., 2018). In Africa, several studies have associated land use and climate change with the aggravation of existing conflicts between farmers and herders sharing common water resources (Link et al., 2015). Migration and conflict are closely linked, as the former can be a major trigger for the latter by increasing pressure on resources and people in the receiving area (Link et al., 2015).

4 | DISCUSSION

The wellbeing of 3.2 billion people around the world is in question due to land degradation (LPH, 2018). The human socio-ecological impacts of land degradation due to climate change will likely grow with time. The results of numerous studies make it clear that climate change-induced land degradation hampers many aspects of health, well-being, and equity, as well as the safety of the natural environment in which humanity can flourish.

Land is defined as "...the terrestrial portion of the biosphere that comprises the natural resources (soil, near-surface air, vegetation and other biota, and water), the ecological process, topography, and human settlements and infrastructure that operate within the system" (IPCC, 2019, p. 349). The relationship between land and human health has been understood since ancient times (Brevik & Sauer, 2015), such that human health is dependent on land through multiple regulatory and provisioning services like clean water, food, shelter, clothing, and fuel (Brevik et al., 2019).

Land degradation is considered to be a crawling, often slow-onset phenomenon comprised of many factors (Vlek et al., 2008). In future climate change scenarios, land will further degrade due to climate change impacts (Vlek et al., 2017), and continuously changing climatic conditions will influence further land degradation around the world. For example, under future climate change scenarios, temperatures will increase across the globe as shown in Figure 3a, especially in and around tropical and subtropical zones. This will have impacts on the high to moderate land degradation index (GLADIS) (see Figure 3b), which is based on the six land degradation process indicators of biophysical and socioeconomic systems: (1) biomass, (2) soil health, (3) water resources, (4) biodiversity, (5) economic, and (6) socio-cultural conditions (Nachtergaele et al., 2010). The impact of increasing temperature on these indicators will create significant pressures on the functions of human socio-ecological systems (Nachtergaele et al., 2010) in these zones.

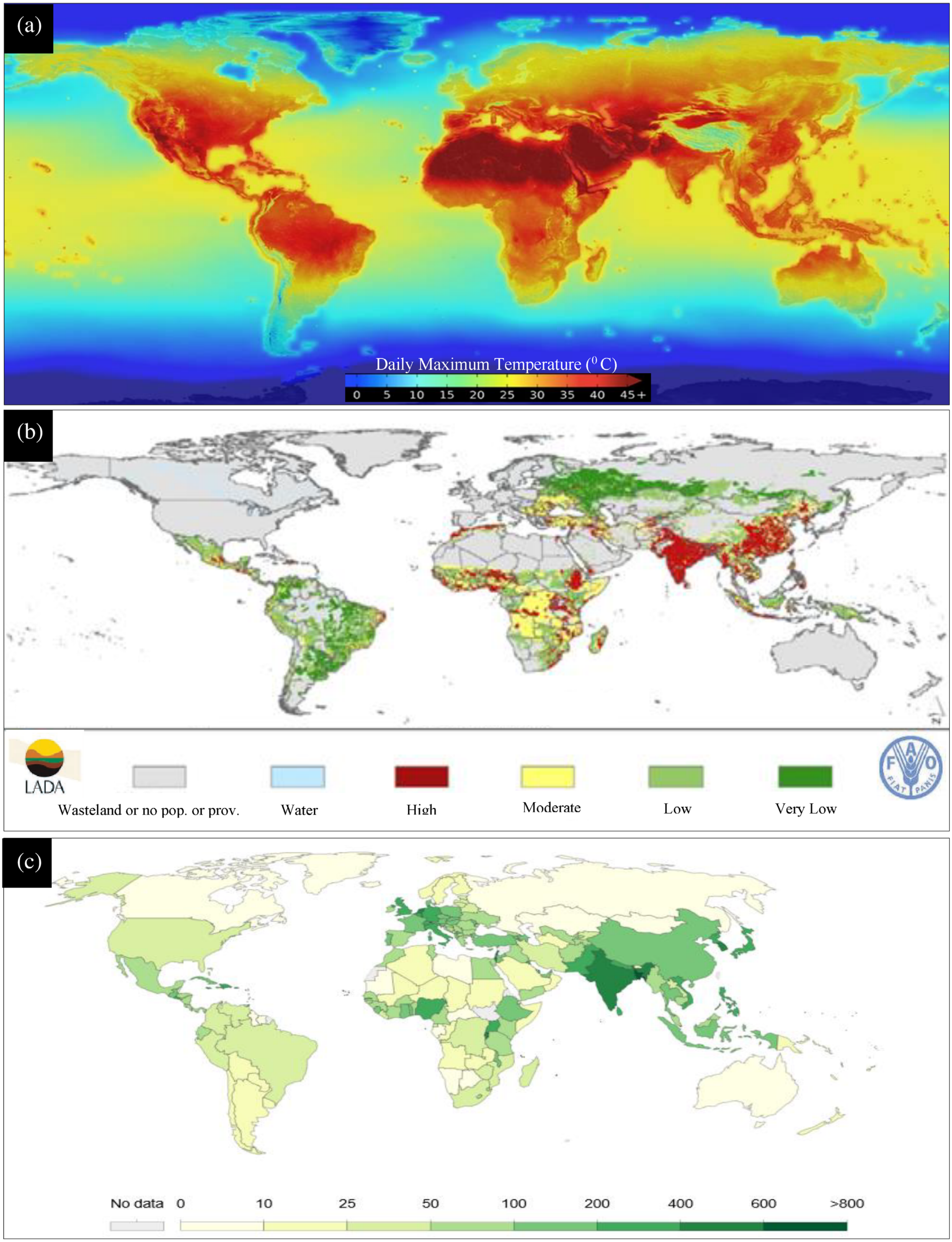

FIGURE 3 (a) Global temperature change up to 2100. Summer maximum temperatures for a global temperature increase of 2.7°C by 2100 from 1850, which will be 4.7°C after 2100 (NASA, 2015). (b) Global state of land degradation as of 2010 (UN-SPIDER, 2019). (c) Global population density (the number of people per km^2 of land area) as of 2017 (Ritchie, 2019) [Colour figure can be viewed at wileyonlinelibrary.com]

Ecosystem functions in tropical soils are more vulnerable to changes in precipitation than temperature. Afreen et al. (2019) found that moist and dry ecosystems respond differently to changes in precipitation since precipitation affects the soil's wet-dry cycle and functions and the processes of ecosystems. Increasing pressure on the GLADIS indicators will expose humans to many planetary health effects. These effects will be stronger for the majority of the world population who live in the tropical and subtropical zones of the Northern Hemisphere (see Figure 3c).

Land is associated with all 17 UN Sustainable Development Goals (SDGs) in multiple research studies (Barbier & Hochard, 2018; Bonfante et al., 2020; Wan Mahari et al., 2020). However, land degradation has a particularly negative influence on SDG2 (zero hunger), SDG3 (good health and well-being), SDG6 (clean water and sanitation), SDG12 (responsible consumption and production), SDG13 (climate action), and SDG15 (life on land), as shown in Figure 4. These influences will make it difficult in many places to achieve SDGs and maintain planetary health. This is why calls to action from both developing and developed countries to "...protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" are specifically emphasized in SDG15.

There are synergies between land degradation and the fulfillment of SDGs (IPBES, 2018). Therefore, the complex adaptive systems inherent in the interlinkages between climate change, land degradation, planetary health, and the SDGs must be clearly understood and assessed (Barbier & Hochard, 2018) to address planetary health issues related to land degradation. The DPSEE framework is a useful tool in this regard.

As a vital natural resource and a global asset, land requires global action which can be achieved through a global target like the land degradation neutrality (LDN) target setting programme, which is a framework to manage land degradation sustainably and equitably. Thus far, 127 countries have joined the programme (UNCCD, 2014; IPBES, 2018; Sims et al., 2019). "The LDN targets address SDG target 15.3 and many other SDGs in a synergistic and cost-effective manner, and in accordance with countries' specific national contexts and development priorities. These targets also strengthen the implementation of the countries' UNCCD National Action Programmes" (UNCCD, 2014).

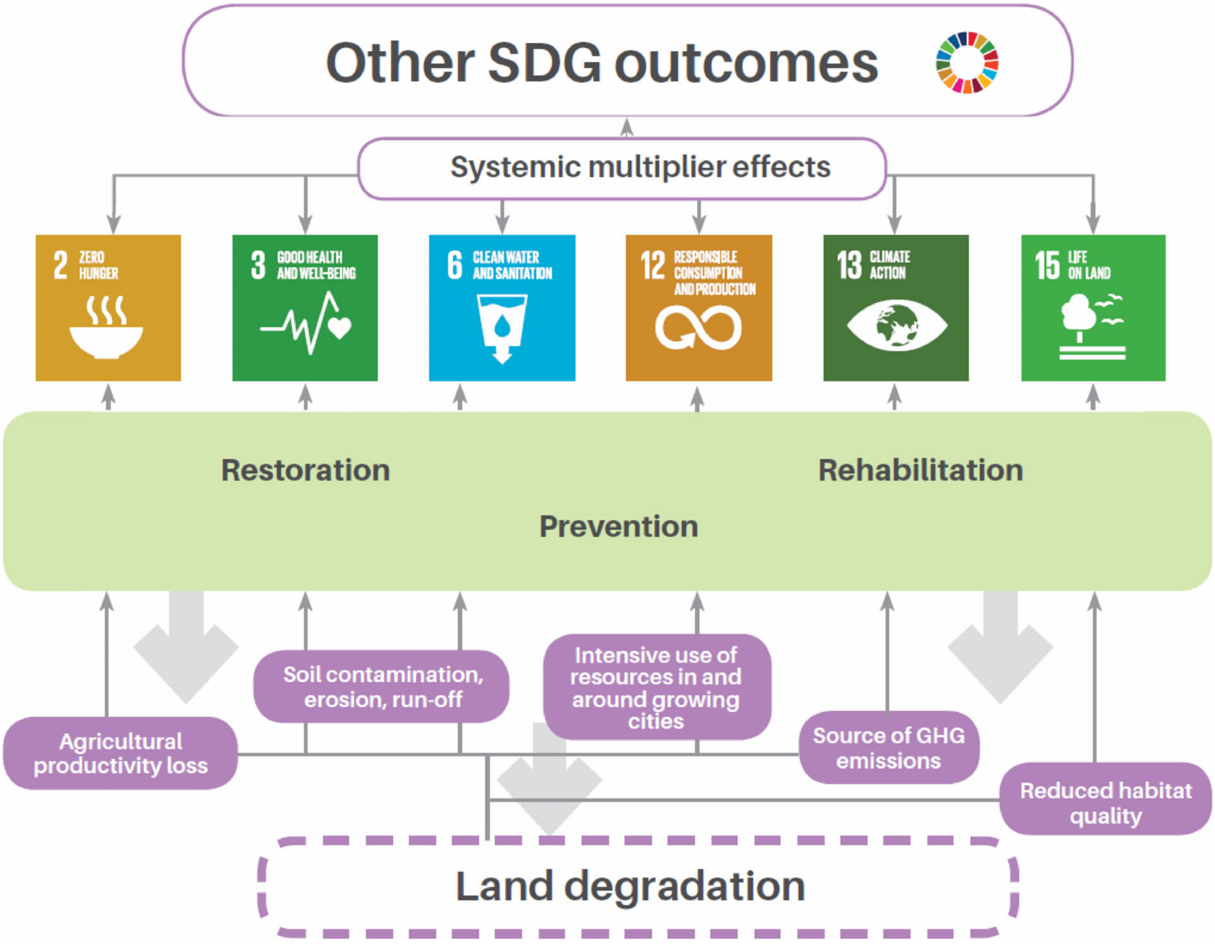

FIGURE 4 Functional links between land degradation and the most directly affected SDGs. *Source*: UNCCD, 2017 [Colour figure can be viewed at wileyonlinelibrary.com]

5 | CONCLUSIONS

Using a pre-defined protocol, a systematic literature search was conducted in Web of Science and Google Scholar to find peer reviewed as well as gray literature on the association of land degradation and planetary health in the context of anthropogenic climate change. Our findings clearly illustrate that anthropogenic climate change and land degradation have been more extensively researched separately than in terms of their links with planetary health. In the literature, climate change-induced soil degradation and its impact on food security have been more popular topics compared to other planetary health impacts described in the results section.

The findings of this study described in the DPSEE framework can help policymakers to better understand the complex pathways of climate change-induced land degradation and its planetary health impacts. The findings also reveal the critical need for a complex system-based approach to understanding the causal relationships and importance of integrated actions to mitigate the planetary health impacts of climate change-induced land degradation.

Land is a limited resource, subject to a myriad of climatic and anthropogenic pressures. Land degradation, climate change, and planetary health interact with each other in a complex system. Therefore, this study has the potential to be a resource for achieving sustainable land management practices and sound planetary health by integrating key scientific knowledge and using a systems-based approach to target the dissemination of critical information on the climate change-land degradation-planetary health nexus beyond the world of academia.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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