Chapter

Forest Degradation in Dryland Ecosystems of Sudan: Review of the Causes, Consequences, Assessment Methods, and Potential Solutions

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Abstract

Dryland forests are ecologically and socioeconomically important. They contribute to livelihood diversification, food security, animal feed and shelter, and environmental conservation in sub-Saharan Africa, particularly Sudan. Despite their importance, current findings show that multiple ecological, human, socio-economic, and policy factors have damaged these resources. As a result, undesirable consequences have been observed, such as food famine, land and water resource degradation, decline/loss of biodiversity, and contribution to global warming that affect the welfare of humans, plants, animals, and micro-organisms. This chapter briefly reviews the forest degradation in drylands Sudan with emphasis on its common causes, impacts, assessment methods, management intervention efforts, and potential future solutions. Given the current situation, there must be urgent combating efforts to manage Sudan's dryland forest resources properly. On the one hand, following prevention measures to essentially deal with the current causes thus prevent any further degradation of forest resources in dryland Sudan. On the other hand, there is an urgent need to address current degradation following appropriate and timely rehabilitation interventions. We also recommend adopting a serious monitoring and evaluation system within these combating efforts by applying the five common indicators for measuring forest degradation: biodiversity, productive functions, carbon storage, forest health, and protective functions.

Keywords: forest degradation, dryland ecosystems, causes of degradation, assessment methods & indicators, management interventions

1. Introduction

Forest resources in drylands hold significant socio-economic and ecological value, especially in sub-Saharan countries like Sudan. Here, they play vital roles in livelihood diversification, food security, animal feed, shelter, and environmental conservation. Despite their importance, recent studies reveal that these resources are undergoing severe degradation due to a complex interplay of natural, anthropogenic, socio-economic, and policy-related factors [1–3]. Forest degradation is a global issue that contributes to deforestation, desertification, and loss of biodiversity, particularly in drylands [4, 5]. Estimates suggest that approximately 850 million hectares of forests and forest lands are degraded [6, 7]. Drylands, which occupy 41% of Earth's land area, have already seen 10–20% degradation, with 1–6% of their populations living in desertified areas [8, 9]. Dry forests constitute more than 40% of all tropical forests [10, 11]. In Africa and tropical islands worldwide, dry forests account for 70–80% of forested areas. These ecosystems are characterized by their seasonality, differing significantly from rainforests, which remain stable year-round [12]. Due to their accessibility and fertility, dry forest zones have historically been preferred for human settlement over wetter forest zones [10–13]. However, this has led to extensive exploitation of these forests for thousands of years, including for fuelwood and charcoal production [14, 15]. In Sudan, forest resources are inversely proportional to population density. A staggering 68% of Sudan's forests are located in the south, where only 15% of the population resides. In contrast, the more populated northern states hold just 32% of the forests [16–19]. The 2015 National Biodiversity Strategy and Action Plan (NBSAP) showed that forest cover accounts for a mere 11.9% of the country, with an annual deforestation rate exceeding 2.4%. The dry tropics are characterized by shifting cultivation systems with both long cultivation and short fallow periods, which hamper the natural recovery of vegetation [20, 21]. Despite their long history of exploitation and the associated degradation, dry forests have received scant attention compared to rain forests. Knowledge gaps make the management and restoration of these forests a challenge, with little data available on forestry activities, stock assessment, and the economic contributions of these resources [20, 21]. In this review, we shed light on the issue of forest degradation in Sudan's drylands. We focus on internationally recognized indicators of forest degradation, its causes, and its socio-economic and environmental consequences. We also propose a set of recommendations for preventing, controlling, and reversing forest degradation as a direction for future research and policy.

2. Concept and signs of forest degradation

Teketay [22] defines forest degradation as alterations within a forest that negatively impact its structure and function, thereby reducing its ability to supply products and/or services. In practical terms, however, the concept of degradation is far more subjective, as perceptions can vary widely regarding the same landscape. Various definitions of forest degradation have been examined through literature reviews, and these are summarized below. The criteria used to define forest degradation differ among authors and international bodies, as highlighted by [23]. This divergence in definitions further emphasizes the subjectivity inherent in understanding and assessing forest degradation, making it a complex and nuanced issue that requires comprehensive, multi-dimensional approaches for effective management and mitigation (**Table 1**).

Overall, a common thread in most definitions of forest degradation found in the literature is the emphasis on reduced crown cover and loss of biodiversity as key indicators. These two elements often serve as crucial signs pointing to the declining health and function of a forest, thus making them vital parameters for evaluating the extent and severity of forest degradation. This consensus provides a starting point for a more unified approach to monitoring and mitigating the issue, despite the various nuances and subjectivities involved in defining forest degradation.

3. Causes of drylands' forest degradation

Despite the immense value and services that forest ecosystems offer in drylands, these vital resources face numerous threats that contribute to their degradation. The literature has extensively discussed the types and categories of factors leading to forest degradation. Generally, there seems to be a consensus to classify these factors into natural and anthropogenic categories [38].

Additionally, the causes of dryland forest degradation (DFD) span multiple dimensions, including economic, social, ecological, policy, and governance factors. These causes can further be categorized under natural influences as well as human-induced (anthropogenic) and social and policy-related factors. This multi-faceted nature of the drivers behind DFD underscores the need for an integrated approach that addresses each of these dimensions to effectively manage and mitigate the degradation of these critical ecosystems.

3.1 Natural factors of forest degradation

Natural factors contributing to dryland forest degradation (DFD) can be further subdivided into:

Parameter	**References covering the parameters**
Changes within the forest	
Structure	[6, 17, 23–27]
Crown cover	[14, 16, 23, 28–32]
Species composition	[12, 16, 17, 23, 26]
Biodiversity	[12, 17, 23, 25]
Stocking	[23, 25, 26]
Soil degradation	[23, 26]
Trees density	[27]
Forest health	[23]
Reduction of capacity to provide	
Productivity	[6, 22, 23, 27, 32–35]
Goods	[6, 23, 25, 26, 28]
Services	[6, 23, 25, 26, 28]
Wood	[6, 25].
Carbon stocks/biomass	[23, 26, 29, 36, 37].
Other functions	[12, 23, 25, 26, 36]

Sources: Adopted from [23].

Table 1.
Parameters covered by different definitions of forest degradation from the literature review.

- *Physical environmental factors*: These include bushfires, challenging topographical conditions such as sloping terrain, and erosion caused by both wind and water. Soil fertility decline also plays a part, often associated with physical problems like low organic matter content, salinity, and alkalinity.
- *Climatic factors*: Insufficient and variable rainfall, unpredictable variations in rainfall patterns both within and between seasons, and intermittent but severe drought conditions all adversely affect the natural regeneration of both indigenous and plantation forests.
- *Biological factors*: These encompass diseases and pest infestations, which may lead to forest fires in extreme cases. For instance, pest outbreaks in lowlands can result in the burning of forests and woodlands, thereby constraining tree-planting efforts. Additionally, aggressive invasive perennial plants and termite attacks can significantly harm the forest ecosystems.

Each of these categories poses unique challenges for the preservation and restoration of dryland forests, and understanding them is crucial for the formulation of effective management and mitigation strategies.

3.2 Anthropogenic factors of forest degradation

Major anthropogenic factors contributing to dryland forest degradation include:

- *Deforestation*: This involves the destruction, clearing, or incineration of dryland forests and woodlands for several reasons: a) Expansion of crop cultivation, driven by a rising human population and limited economic diversification options. b) Production of charcoal and wood for domestic energy needs, due to a lack or shortage of alternative energy sources, as well as for construction materials and carpentry items. These resources are also often sold to generate income and support household livelihoods. c) Immediate socio-economic and infrastructural development needs, such as resettlement, mining, and road construction.
- *Overgrazing/grazing by livestock*: Overgrazing leads to soil compaction and damage to seedlings, hampering natural regeneration processes.
- *Unsustainable utilization*: This includes improper and unplanned harvesting practices, which result in significant wood wastage due to extremely low recovery rates and damage to the residual trees, plants, and stands.
- *Introduction of invasive alien species*: The introduction of non-native species can lead to the displacement of native dryland forest flora and, by extension, the reduction in overall biodiversity.

Each of these anthropogenic factors poses its own set of challenges to the health and sustainability of dryland forests. Addressing them will require multi-faceted and tailored approaches that take into account the complexity and interconnectedness of these contributing elements.

4. Socio-economic and policy-related factors

According to Teketay [22], several socio-economic and policy-related factors contribute either directly or indirectly to the degradation of dryland forests. The major factors among these include:

- *Poverty, population growth, and poor economic performance*: These interconnected factors exacerbate the pressure on dryland forests as communities rely more heavily on forest resources for their livelihoods.
- *Inadequate or absence of land-use classification and forest policies*: The lack of clear land-use classification, along with insufficient or absent forest policies and legislation, leaves forests vulnerable to exploitation and degradation.
- *Absence of land and tree tenure/ownership rights*: Without clear rights to land or trees, there's little incentive for individuals to manage forests sustainably.
- *Underestimation of dryland forests' contribution*: The economic and ecological value of dryland forests often goes unrecognized, leading to policy neglect.
- *Lack of pricing and incentive policies*: Without economic incentives or appropriate pricing mechanisms, sustainable forest management practices are rarely adopted.
- *Inadequate institutional arrangements*: Weak organizational structures and governance mechanisms can hinder effective forest management.
- *Absence or inadequacy of viable dryland forestry development strategies*: The lack of long-term planning and investment in sustainable forestry initiatives contributes to ongoing degradation.
- *Weak forestry research systems*: Insufficient research into sustainable forestry practices limits the development of effective forest management techniques.
- *Insufficient information management*: A lack of comprehensive and accessible data hampers the planning and execution of sustainable forestry initiatives.
- *Political instability*: Civil wars, unrest, and other forms of political instability can result in short-term exploitation of forests at the expense of long-term sustainability.

Understanding and addressing these socio-economic and policy-related factors is crucial for developing multi-pronged strategies to manage and mitigate dryland forest degradation effectively.

5. Consequences of dryland forest degradation

The impacts of dryland forest degradation are multi-dimensional and significantly detrimental to both the environment and human livelihoods. Here are some key consequences:

1. **Environmental consequences:**

    - *Wood famine:* Over-exploitation of forest resources leads to a wood deficit, which can prompt communities to "mine" forests, i.e., to harvest wood at rates exceeding the forest's capacity for natural regeneration [22].

    - *Land degradation:* This refers to both soil erosion and loss of soil fertility. Often, metrics used to assess land degradation focus on the severity of soil erosion, which can be particularly acute in areas with high-intensity rainstorms and steep slopes [39, 40].

    - *Degradation of water resources:* Poor land management can lead to sedimentation and siltation in water bodies. Deforestation and soil erosion increase surface runoff, reducing the soil's capacity to absorb and store water, affecting groundwater levels and overall water availability [22, 41].

    - *Decline of biodiversity:* Reduced vegetation cover and invasion by alien species undermine the ecological health of dryland forests, leading to a decline in both flora and fauna. Loss of biodiversity affects valuable non-timber forest products (NTFPs), such as wild foods, medicine, and materials for crafts, that communities rely on [22, 42].

    - *Enhanced global warming:* Deforestation contributes to greenhouse gas emissions, exacerbating global warming. Additionally, forests act as carbon sinks, and their degradation means less carbon is being sequestered from the atmosphere [37, 43, 44].

2. **Socio-economic consequences:**

    - *Food and livelihood security:* The degradation of dryland forests threatens food security by reducing the availability of wild foods and other forest resources that rural communities rely on.

    - *Economic value:* Forests offer various forms of livelihood, from timber to non-timber forest products like resins, gums, and honey. Forest degradation diminishes these opportunities, impacting the local and national economies.

    - *Public health:* Poor water quality from sedimentation and reduced availability of medicinal plants can have implications for public health.

    - *Cultural and spiritual value:* Many communities have deep cultural and spiritual connections to forests, and degradation can result in the loss of these important aspects of human well-being.

To address these challenges, a multi-faceted approach is needed that combines sustainable forest management practices, socio-economic interventions, and policy changes. This should also involve the active participation of local communities and be guided by comprehensive research and monitoring (**Figure 1**) [45].

This diagram illustrates the complex interplay of processes contributing to forest degradation in the Brazilian Amazon. The framework begins with pristine forests that

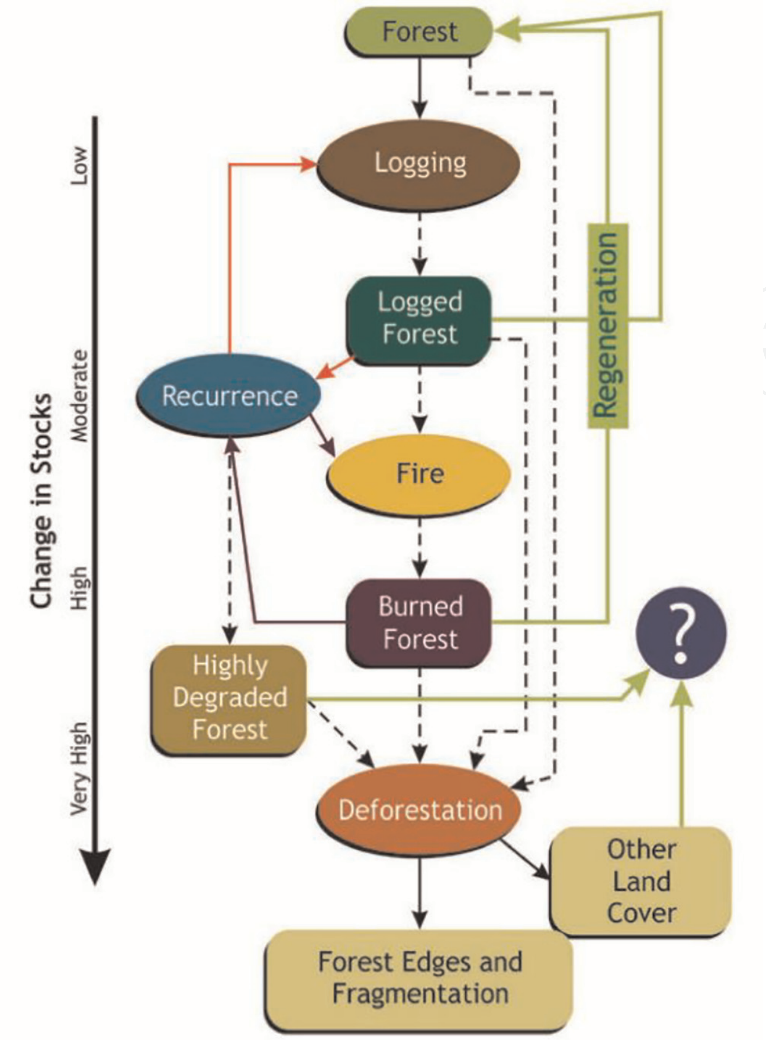

Figure 1.
Dynamics and interactions of forest degradation [45].

become vulnerable through several stages that are mentioned in the diagram and seeks to encapsulate the chain reactions and feedback loops involved in forest degradation, emphasizing the multifaceted nature of the issue.

Figure 2 presents a detailed look at the far-reaching implications of forest cover loss. At its core, the loss of forest cover serves as a catalyst for a cascade of negative environmental, social, and economic consequences. The environmental impacts are immediate and devastating, affecting biodiversity, soil quality, and the water cycle. This leads to a decrease in carbon sequestration capabilities, which further exacerbates climate change. On a social level, forest cover loss adversely affects indigenous communities and local populations that rely on forests for their livelihoods, leading to displacement and poverty. The economic repercussions are equally severe, with the loss of valuable resources like timber, non-timber forest products, and ecosystem services that have both local and global economic value. The figure also illustrates how these different domains are interlinked, emphasizing that the implications of forest cover loss are not isolated but are interconnected in complex ways. Therefore, forest cover loss represents a multidimensional issue that requires integrated solutions.

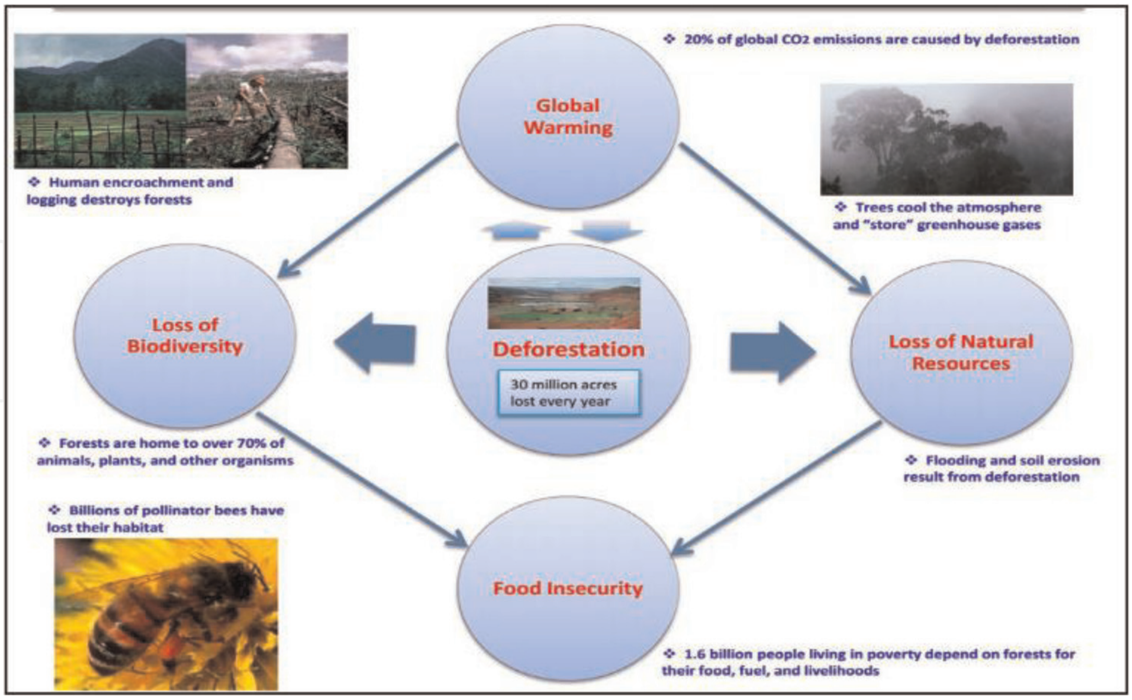

Figure 2.
Implication of forest cover loss [17].

6. Methods of assessing forest degradation and common indicators

There are two common methods for assessing forest conditions which are briefly stated in the following:

6.1 Remote sensing-based multi-temporal analysis

Advancements in modern technology have been a boon to the field of environmental science, particularly in the realm of forest conservation and management. Among these technologies, remote sensing stands out as a particularly effective method for long-term monitoring of forest conditions. Developed over the years through various studies [44, 46, 47], remote sensing technologies now allow for sophisticated multi-temporal analyses that can reveal subtle but significant changes in forest ecosystems.

In the multi-temporal analysis approach, satellite images of the same geographical location are captured at different times and are then aligned or 'co-registered' with one another. This enables scientists to directly compare these images, paying particular attention to changes in spectral values, which are indicative of shifts in vegetation condition and health. Spectral values are measures of how different wavelengths of light are absorbed or reflected by the Earth's surface, providing a sort of 'fingerprint' of its current state. For instance, healthy vegetation reflects a lot of green light but absorbs red and blue light, which is why it appears green to the human eye. By studying these spectral "signatures," experts can glean intricate details about soil moisture levels, plant health, and even species composition.

The utility of this approach has been demonstrated in various settings, including the ability to monitor specific types of environmental stress. For example, the analysis of multi-temporal imagery has proven to be particularly effective for tracking defoliation events caused by insect infestations [48]. Such defoliation would show up as changes in the spectral values, allowing researchers to not only identify affected areas quickly but also estimate the extent of foliage loss. This is invaluable information for forest management teams who can then take targeted action, whether it be through the introduction of natural insect predators or other integrated pest management strategies.

Moreover, multi-temporal remote sensing offers the advantage of continuous, automated monitoring, enabling timely interventions. It's an approach that makes it possible to identify patterns and trends over time, from seasonal variations to the long-term impacts of climate change. This not only facilitates proactive management practices but also aids in policy formulation for sustainable forest management.

While remote sensing provides a bird's-eye view of large forested areas and can quickly detect large-scale changes, it's important to combine this method with ground assessments for a more comprehensive understanding. On-the-ground assessments can validate satellite imagery findings while adding context, especially when it comes to local biodiversity, soil conditions, and human activity. Therefore, the integration of both remote sensing and ground-based methods offers the most thorough, accurate, and actionable insights for forest conservation efforts.

6.2 Ground assessment of vegetation conversion and change

In addition to the technological advances of remote sensing, direct field or ground assessments serve as another crucial method for monitoring and evaluating forest conditions. Unlike remote sensing, which offers a macroscopic, overhead perspective, ground assessments provide a microscopic, detailed view that is indispensable for a comprehensive understanding of forest ecosystems.

Ground assessments typically involve systematic vegetation sampling to evaluate key metrics such as species composition, abundance, distribution, and structural attributes of the forest. Essentially, researchers collect baseline data for these parameters and then periodically revisit the site to identify any changes. This approach is cited as particularly effective for assessing forest degradation, offering nuanced insights that remote sensing sometimes misses [45, 49, 50].

During these ground assessments, various indicators can be meticulously examined. For instance, vegetation composition can be assessed through species identification and counts, helping to determine if invasive species are encroaching upon native vegetation. Abundance and distribution metrics can indicate whether certain species are becoming more dominant or rare, possibly signaling ecological imbalance. Structural attributes, such as tree height, canopy density, and undergrowth conditions, can provide clues to the forest's overall health and its ability to support various forms of wildlife.

Importantly, ground assessments also allow for the study of soil conditions, local hydrology, and even microclimatic variables, offering a holistic perspective on the forest ecosystem. Soil samples can reveal nutrient deficiencies, contamination, or changes in microbial communities, all of which have far-reaching implications for vegetation health. Examination of local water sources can also identify any changes in water quality or quantity, which again impacts the entire ecosystem.

Additionally, ground assessments can be designed to be adaptive, allowing researchers to adjust their monitoring strategies based on preliminary findings or

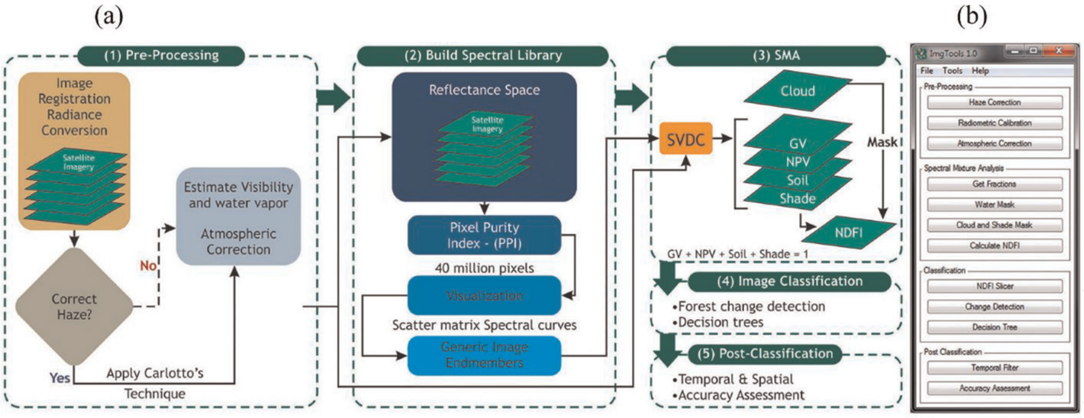

Figure 3.
Conceptual framework of the image processing procedures: a) pre-processing, b) software [45].

emerging environmental threats. This adaptability ensures that the assessment remains relevant and continues to generate actionable data over time.

While ground assessments are generally more labor-intensive and time-consuming than remote sensing methods, they offer an unparalleled level of detail. Therefore, the most effective forest monitoring programs often employ a multi-faceted approach, combining the broad overview provided by satellite imagery with the granular detail captured through ground assessments. This integrated methodology ensures a more accurate and nuanced understanding, which in turn facilitates better decision-making for conservation and management efforts (**Figure 3**).

6.3 Common indicators of forest degradation in dryland ecosystem

Forest degradation has been succinctly defined as a reduction in the ability of a given forest ecosystem to provide goods and services [51]. A comprehensive framework was first established in 2009 and has been globally adopted to measure forest degradation, including in dryland areas. This framework consists of five major categories of indicators:

1. *Biodiversity indicators*: These gauge the ecosystem's biological health and include measures like changes in ecosystem diversity, shifts in ecosystem resilience (or state), and metrics related to fragmentation, road density, and the abundance of indicator species. Additional aspects may involve monitoring keystone and flagship species, which can indicate the general state of biodiversity in a specific region.

2. *Productive functions indicators*: These are concerned with the forest's economic and resource potential. They measure changes in the amount of timber products, growing stock for selected species, non-wood forest products, fuelwood, and even water quality and quantity. This also extends to measuring the impact of forest management practices on the productivity of these resources over time.

3. *Carbon indicators*: With a focus on climate change and carbon sequestration, these indicators monitor the amount of total biomass, growing stock, and carbon stored in each of the five carbon pools (above-ground biomass, below-ground biomass, litter, deadwood, and soil organic carbon). They may also incorporate

additional measures like changes in leaf area index, which can provide insights into the forest's ability to sequester carbon.

4. *Forest health indicators*: This category addresses the forest's vulnerability to both biotic (living) and abiotic (non-living) agents, such as fires, diseases, invasive species, storms, and snowfall. Sub-indicators include:

6.3.1 Crown condition

The crown indicator serves as a comprehensive measure to evaluate the health and vitality of individual trees within a forest ecosystem. It specifically focuses on three main components: the amount of foliage, the condition of that foliage along with branches, and the distribution of growing tips on the trees. By assessing these components, one can derive valuable insights into not only the health of individual trees but also the overall health and resilience of the forest.

1. *Amount of foliage*: The density and amount of leaves or needles on a tree can provide essential information about its nutritional status, potential for photosynthesis, and by extension, its general health. Sparse or discolored foliage may indicate nutritional deficiencies, disease, or environmental stressors affecting the tree.

2. *Condition of foliage and branches*: The physical state of the leaves and branches, including signs of disease, insect damage, or physical injury, can reveal the immediate challenges facing a tree. This could range from pests and pathogens to environmental stressors like drought or pollution.

3. *Distribution of growing tips*: The presence and distribution of growing tips, or meristems, can offer insights into the tree's reproductive potential and future growth. An imbalance in the distribution might suggest that the tree is experiencing stress or has been affected by external factors like pruning or damage.

   Together, these aspects offer a nuanced picture of trees and, by extension, forest health. They can be invaluable for early detection of forest degradation factors such as disease outbreaks or the impact of environmental stressors. Given their significance, crown indicators have been elaborated extensively in academic and practical literature, serving as a cornerstone in the study and monitoring of forest ecosystems [52].

6.3.2 Lichen communities

Lichens, the symbiotic organisms resulting from the partnership between fungi and algae, are a remarkable component of many forest ecosystems. They colonize various surfaces, including the bark of trees, rocks, and even soil, thereby playing multiple crucial roles within these ecosystems.

1. *Nutrient cycling*: Lichens are particularly effective at breaking down rocks and other hard substrates, contributing to the formation of soil and the cycling of essential nutrients. This process is critical for the ongoing productivity and health of forest ecosystems.

2. *Wildlife habitat and forage*: Numerous small animals and insects rely on lichens for both habitat and food. For example, lichens serve as nesting materials for birds and offer a vital winter food source for some species of herbivores.

3. *Environmental indicators*: Lichens are highly sensitive to various environmental factors, including the quality of the air. Their physiology allows them to absorb nutrients and moisture directly from the atmosphere, which also makes them vulnerable to pollutants. Therefore, changes in lichen communities can be an early warning sign of deteriorating air quality or other ecological stresses.

4. *Climate change indicators*: Lichens have also been found to be highly responsive to changes in climate, including temperature and humidity variations. Their presence or absence can serve as a valuable barometer for assessing long-term climate trends and their impact on forest ecosystems.

   Given their multi-faceted contributions and sensitivity to environmental conditions, lichens serve as an invaluable bio-indicator for forest health and vitality. Monitoring the diversity, abundance, and condition of lichens can provide a wealth of information about the forest's current state and its resilience to future changes or threats. This concept of using lichens as an indicator has been described extensively, providing a foundational tool for ecologists, conservationists, and researchers interested in forest health and sustainability [53].

6.3.3 Down woody debris

Down Woody Debris (DWD) serves as an often-overlooked yet invaluable metric for assessing the health, complexity, and functionality of a forest ecosystem. This indicator involves the meticulous cataloging and analysis of various forms of woody material that have fallen to the forest floor, ranging from smaller twigs to entire tree trunks.

1. *Classification by size*: DWD is typically divided into two main categories based on size. Smaller fragments with diameters less than 3 inches are classified as "fine woody debris," while larger branches and entire fallen trees are termed "coarse woody debris."

2. *Species identification*: Documenting the species of the downed woody material can offer critical insights into the forest's biological diversity and the specific types of trees that may be more susceptible to disease, pests, or environmental stresses.

3. *Shape, size, and decay*: The varying shapes, sizes, and stages of decay are also recorded. These characteristics not only help in assessing the rate of decomposition and nutrient cycling but also offer clues about the forest's history and the ecological processes at play.

4. *Habitat and ecological importance*: DWD serves multiple ecological roles. It provides habitat for a range of organisms, from fungi and insects to larger mammals. It's also a critical component in the forest's nutrient cycle, as it decomposes to release essential minerals back into the soil.

5. *Monitoring decay and environmental change*: The rate of decay can reveal information about climatic conditions such as moisture levels and temperature, making DWD a useful proxy for monitoring environmental change over time.

6. *Safety and fire risk*: Excessive DWD can pose fire risks in certain conditions. Therefore, monitoring DWD levels can be essential for forest management, especially in regions prone to wildfires.

7. *Data-driven forest management*: Accurate DWD measurements contribute to more effective forest management practices, helping resource managers make informed decisions regarding activities like controlled burns, logging, and conservation efforts.

   By meticulously examining and cataloging Down Woody Debris, researchers and forest managers can glean a multitude of insights about the ecosystem's health, its history, and its capacity to support various forms of life. These aspects of the DWD indicator have been discussed in great depth, offering a nuanced tool for understanding and managing forest ecosystems [54].

6.3.4 Tree damage

The Damage Indicator serves as a comprehensive gauge for evaluating the various impacts affecting the health and vitality of a forest ecosystem. This measure delves into the nuances of forest health by meticulously recording different types of injuries and their causative agents. By doing so, it allows for a more granular understanding of forest health, thereby aiding in targeted conservation and management efforts.

1. *Types of damages*: The indicator categorizes damages into multiple types, ranging from diseases and pest infestations to weather events like storms and human-induced injuries such as logging or accidental fires.

2. *Severity and extent*: It's not just about identifying the types of damage but also evaluating their severity and extent. For instance, the spread of a specific canker disease through a tree stand may be mapped and classified based on how debilitating it is to the trees.

3. *Localization*: Pinpointing the exact location of the damage within the forest and even within individual trees (e.g., trunk, roots, or branches) offers more actionable data for remedial measures.

4. *Recording specific ailments*: Data collection extends to specific symptoms such as open wounds, signs of advanced decay, cankers, and structural damages like broken boles and roots. Each of these parameters can indicate a different set of environmental stressors or diseases affecting the forest.

5. *Monitoring over time*: Tracking these damage metrics over a period allows forest managers to spot trends or spikes in forest health issues, enabling timely interventions.

6. *Impact on ecosystem services*: Understanding the types and extents of damages is crucial for assessing the forest's capacity to continue providing ecosystem services, whether they are in the form of timber, non-wood forest products, or even intangibles like air and water purification.

7. *Data-driven decision making*: By compiling this intricate data, forest managers and policymakers can make more informed decisions, whether it's implementing disease control measures, modifying logging practices, or planning restoration activities.

8. *Emergency response*: In cases of sudden and severe damage, like that caused by storms or pest outbreaks, this indicator can be crucial for orchestrating rapid and effective response strategies.

9. *Public awareness and education*: Publishing findings related to the Damage Indicator can also serve an educational role, informing the public about the state of their local forests and the importance of responsible stewardship.

   By methodically recording and interpreting these aspects of tree damage, this indicator furnishes a multi-faceted lens through which forest health can be evaluated and managed [55].

6.3.5 Tree mortality

The Tree Mortality Indicator is a crucial metric that offers insights into the overall health and sustainability of a forest ecosystem. It meticulously quantifies the number, size, and volume of trees that have died, thereby furnishing critical data that can illuminate the underlying causes of forest decline. In doing so, it allows for nuanced approaches to forest management and conservation.

1. *Number of trees*: The indicator starts by counting the actual number of trees that have succumbed to death. This count is valuable in assessing the scale of tree mortality within a specific forest or region.

2. *Size and volume*: In addition to the sheer number, the size (diameter at breast height, DBH) and volume of the dead trees provide insights into which age classes or species are more susceptible to certain threats. For example, older trees may be more vulnerable to diseases, while younger ones might be more susceptible to drought.

3. *Categorizing stressors*: The indicator helps identify whether the cause of tree mortality is related to biotic factors like diseases and pests or abiotic factors like drought, fire, or human activity. This categorization aids in devising specific interventions to mitigate future losses.

4. *Stand development and structural changes*: Changes in forest stand composition and structure can lead to altered growing conditions that may become unfavorable for specific tree species or age classes. Monitoring this data can help in forest succession planning.

5. *Indicator of ecosystem health*: High tree mortality rates can signal broader ecosystem instability, affecting not just the flora but also the fauna that depend on them.

6. *Impacts on carbon sequestration*: Tree mortality directly affects the forest's ability to act as a carbon sink. Dead trees release stored carbon back into the atmosphere, thus playing a role in larger climate dynamics.

7. *Adaptive management*: Information from the Tree Mortality Indicator can be used for adaptive forest management strategies. For example, if a certain tree species shows high mortality rates, forest managers may consider planting more resilient species.

8. *Policy implications*: High levels of tree mortality could prompt regulatory changes, such as altering logging quotas or implementing more stringent conservation policies.

9. *Long-term monitoring*: Continual monitoring allows for the tracking of tree mortality trends over time, helping to validate the effectiveness of implemented interventions or the need for new strategies.

10. *Public engagement*: Transparently sharing these mortality statistics can raise public awareness about the health of local forests, thus fostering community engagement in conservation efforts.

Overall, the Tree Mortality Indicator serves as a robust diagnostic tool that helps stakeholders better understand forest dynamics, thereby allowing for more effective and targeted conservation initiatives [56].

6.3.6 Vegetation diversity and structure

The vegetation diversity indicator provides a comprehensive evaluation of forest ecosystems by quantifying the variety, abundance, and spatial arrangement of vascular plant species. This tool serves multiple purposes, including inventory assessment and long-term monitoring. By keeping track of changes in species richness, their relative abundances, and the layering or vertical structure within the forest, it helps researchers and conservationists gauge the health and resilience of the forest over time. This indicator is particularly useful for capturing nuanced shifts in forest composition, which can result from various factors like climate change, habitat fragmentation, or human activity. Additionally, changes in the vertical stratification of vegetation—such as the understory, midstory, and canopy—can indicate the forest's capacity to support a diverse array of wildlife and maintain its ecological functions. This comprehensive approach to understanding vegetation diversity is invaluable for adaptive management strategies, providing a more complete picture of forest health and functioning. For a more in-depth discussion and methodology of this indicator [57].

6.3.7 Soil condition

Soil serves as the foundational component in forest ecosystems, supplying the essential environmental elements upon which all vegetation relies: nutrients for growth, water for sustenance, air for respiration, heat for temperature regulation, and mechanical support for stability. Beyond these basic functions, soil health is intricately linked to a range of forest processes and services, thereby making it a crucial indicator for forest management and conservation. The soil condition indicator provides both chemical and physical data, offering critical insights into the soil's fertility status and its physical characteristics such as texture, structure, and water-holding capacity. These metrics are instrumental in a variety of ecological models, which operate at diverse spatial scales within the forest ecosystem. For instance, accurate soil data can help estimate the forest's carbon budget, thereby assessing its role in carbon sequestration and climate change mitigation. By comprehensively understanding the condition of the soil, researchers and forest managers can make more informed decisions about sustainable land use, reforestation initiatives, and the mitigation of environmental impacts such as soil erosion and nutrient depletion. This deep-dive into soil indicators and their significant role in forest ecology is elaborated upon in the study detailed by [58].

6.3.8 Ozone injury

A subset of plant species serve as particularly sensitive bioindicators of ozone exposure levels that exceed typical background concentrations. These plants display distinct symptoms of foliar injury on the upper surface of their leaves, which sets them apart from other types of foliage damage. Such easily identifiable and quantifiable signs of ozone-induced stress make them invaluable for monitoring air quality and its potential impact on forest ecosystems. By focusing on these bioindicator species, researchers can more precisely gauge the levels of ozone pollution in a given area and understand its ecological implications. This information is especially critical for assessing the health of forest ecosystems that may be affected by rising ozone levels due to industrial activities or other environmental stressors. The presence or absence of these symptoms can serve as a red flag for policymakers and forest managers, enabling them to take timely action to mitigate harmful effects. The intricate dynamics of how ozone levels influence plant health, and by extension, the overall well-being of forest ecosystems, is explored comprehensively in the research elaborated upon by [59].

6.3.9 Protective function indicator which is indicated by the rate of soil erosion (or area affected)

The Protective Function Indicator focuses on assessing the forest's role in soil conservation, particularly by monitoring the rate of soil erosion or the extent of areas affected by it. Soil erosion can lead to the loss of fertile topsoil and decrease the forest's ability to store water and nutrients, adversely impacting its overall health and resilience.

This indicator is crucial because forests often serve as natural barriers against soil erosion, thereby preserving water quality and reducing the risk of landslides and other natural disasters. High rates of soil erosion could signify that the forest's protective functions are compromised, possibly due to factors such as deforestation, uncontrolled logging, or the presence of invasive species that destabilize soil structures.

By closely monitoring the rate of soil erosion and the extent of affected areas, forest managers can take targeted conservation measures, such as reforestation or implementing erosion control structures like terraces or sediment traps.

Understanding the forest's ability or inability to perform this protective function can be pivotal for land-use planning and natural resource management strategies.

The methodology and metrics for assessing the Protective Function Indicator in the context of soil erosion are discussed in detail in the relevant scientific literature, serving as a guideline for both researchers and policymakers in the evaluation of forest degradation and conservation efforts.

7. Prevention and control measures of forest degradation in drylands

Addressing the pervasive issue of forest degradation in drylands necessitates an intensive, multi-faceted approach, given the magnitude and far-reaching implications of the problem. However, merely dealing with the degradation after it occurs is insufficient; it's vital to take into account the intricate web of contributing factors—be they climatic, anthropogenic, or ecological—that feed into this environmental calamity. This involves not just identifying its root causes, but also establishing a comprehensive set of assessment indicators that can measure the degradation's scope, rate, and ultimate impact on both the local ecosystem and broader environmental health.

Beyond immediate control and rehabilitation methods, a proactive, preventive strategy must also be part of the solution. Simply put, measures to halt degradation are not enough; preemptive actions that thwart its onset in the first place are just as crucial. This calls for a shift in perspective, from a reactive to a proactive stance in combating forest degradation.

With this in mind, we propose two key interventions aimed at both effectively halting and preventing forest degradation in drylands:

1. Comprehensive Ecosystem Monitoring: Implement a real-time, data-driven monitoring system that uses advanced technologies like remote sensing, GIS mapping, and predictive modeling. This would not only provide a detailed understanding of the current state of forest health but would also allow for the early detection of signs of degradation. The sooner these signs are detected, the quicker and more effective preventive measures can be taken.

2. Sustainable land management: Introduce land-use policies that are ecologically sustainable, such as agroforestry and controlled grazing, and combine these with community education and involvement. By adopting such integrated approaches, not only can immediate threats be managed, but the local community can also be empowered to act as stewards of their environment, thus ensuring long-term sustainability

7.1 Prevention/mitigation measures:

Addressing the root causes of forest degradation is an intricate task that involves a multi-pronged approach, taking into account not just the environmental aspects but also forest governance, community involvement, and economic factors. This complexity demands a multi-layered solution tailored to specific concerns.

1. **Forest governance:**

    - *Establishing a professional body for foresters*: A dedicated organization can provide guidelines, share best practices, and set ethical standards. This body can serve as a liaison between governmental agencies and local communities.

- *Harmonizing laws*: Streamlining forestry laws can prevent conflicting rules that may result in ineffective management or misunderstandings.
- *Awareness programs*: Conducting educational campaigns to raise awareness about forestry laws can help avoid conflicts and violations.
- *Local NGO involvement*: Encouraging NGOs to incorporate forest conservation programs can augment government efforts in preventing degradation.

2. **Community involvement**:
    - *Community-led forest management*: Empowering local communities to take part in the management of forests not only promotes conservation but can also provide local economic benefits.
    - *Participative monitoring*: Local communities, being the closest to the forest resources, can be vital in monitoring and reporting signs of degradation or illegal activities.
3. **Economic factors**:
    - *Poverty alleviation programs*: Implementing social safety nets and income-generating opportunities can reduce the dependency of families on forest resources for their livelihoods.
    - *Alternative energy sources*: Providing affordable and clean alternative energy options can significantly reduce the unsustainable use of forest resources for fuel.
    - *Regulating timber trade*: A comprehensive system should be in place to combat illegal timber trade and regulate its export.
    - *Recognizing traditional medicine*: Understanding and officially recognizing the value of forest plants for traditional medicine can make sustainable harvesting more economically viable.
    - *Modern agricultural systems*: Implementing modern, sustainable agricultural practices can reduce the pressure exerted on forest land for agriculture.

By focusing on these pillars—governance, community involvement, and economic factors—tailored interventions can be developed to tackle the root causes of forest degradation. Doing so involves not just policy changes but also active collaboration among governments, professionals, communities, and NGOs.

7.2 Control/adaptation measures

To holistically address the challenges of forest degradation in drylands, a multifaceted approach is necessary. Here are some expanded guidelines grouped under specific topics that could pave the way for more sustainable forest management:

1. **National forest programs and eco-agriculture**:
    - *Comprehensive national forest programs*: Creating realistic, yet ambitious, national frameworks can provide a roadmap for long-term forest conservation and restoration.
    - *Introduce eco-agriculture*: Adopting agroecological methods that integrate trees and tree products can offer dual benefits: enhanced agricultural yield and forest conservation.
    - *Develop markets and infrastructure*: Building and standardizing marketplaces for tree products encourages sustainable usage and boosts local economies.
2. **Market exploration and price regulation**:
    - *Explore both domestic and international markets*: Widen the market access for dryland forest products to optimize revenue generation.
    - *Timely market information*: Providing real-time market data can help producers understand demand and get fair prices.
    - *Price regulation*: Ensuring price floors for dryland forest products can make forest conservation more economically viable.
3. **Alternative energy sources**:
    - *Promote non-wood energy*: Encourage the use of energy alternatives like solar, wind, and biogas to reduce dependency on wood, charcoal, and other forest resources.
4. **Integrated and multidisciplinary approach**:
    - *Comprehensive solutions*: Given the complexity of dryland forest degradation, an integrated approach that combines sectoral development with targeted interventions is vital.
5. **Information dissemination and research**:
    - *Organize and publish grey literature*: The knowledge that has been accumulating but remains unpublished should be organized, published, and disseminated for wider benefit.
    - *Valuation of dryland forest products*: Conduct studies to place monetary values on the ecosystem services provided by dryland forests.
    - *Cross-disciplinary research*: Investigate not just the biophysical factors but also the social, economic, and institutional aspects of forest degradation and rehabilitation.

By methodically tackling each of these areas, it is possible to build a comprehensive strategy that not only mitigates the ongoing degradation but also sets a foundation for the sustainable development of dryland forests [60].

Figure 4 presents a comprehensive conceptual framework that delineates the intricate relationship between the causes and consequences of land degradation, as

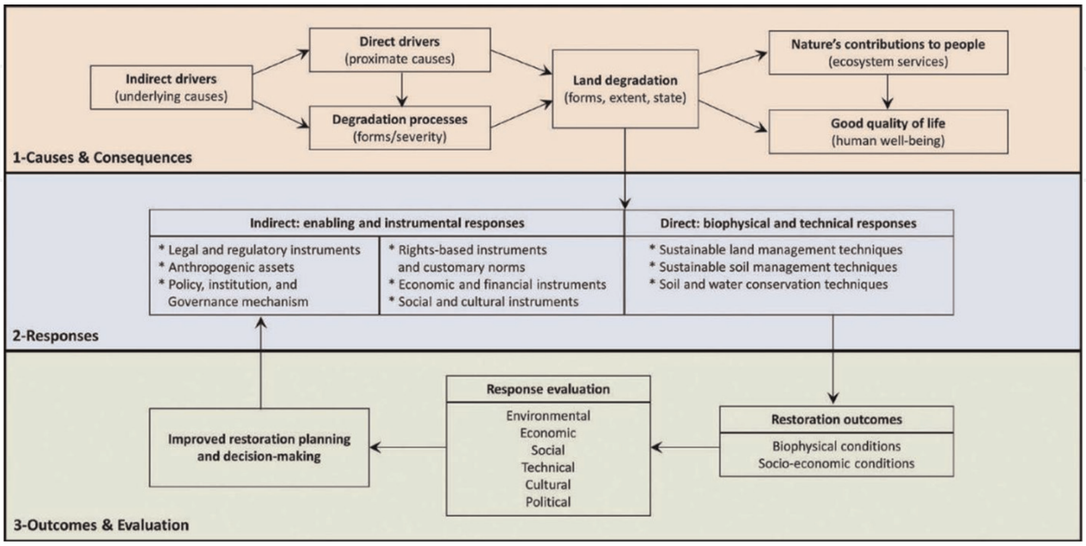

Figure 4.
Conceptual framework linking land degradation causes and consequences, restoration responses (both indirect and direct), and response outcomes and evaluation [60].

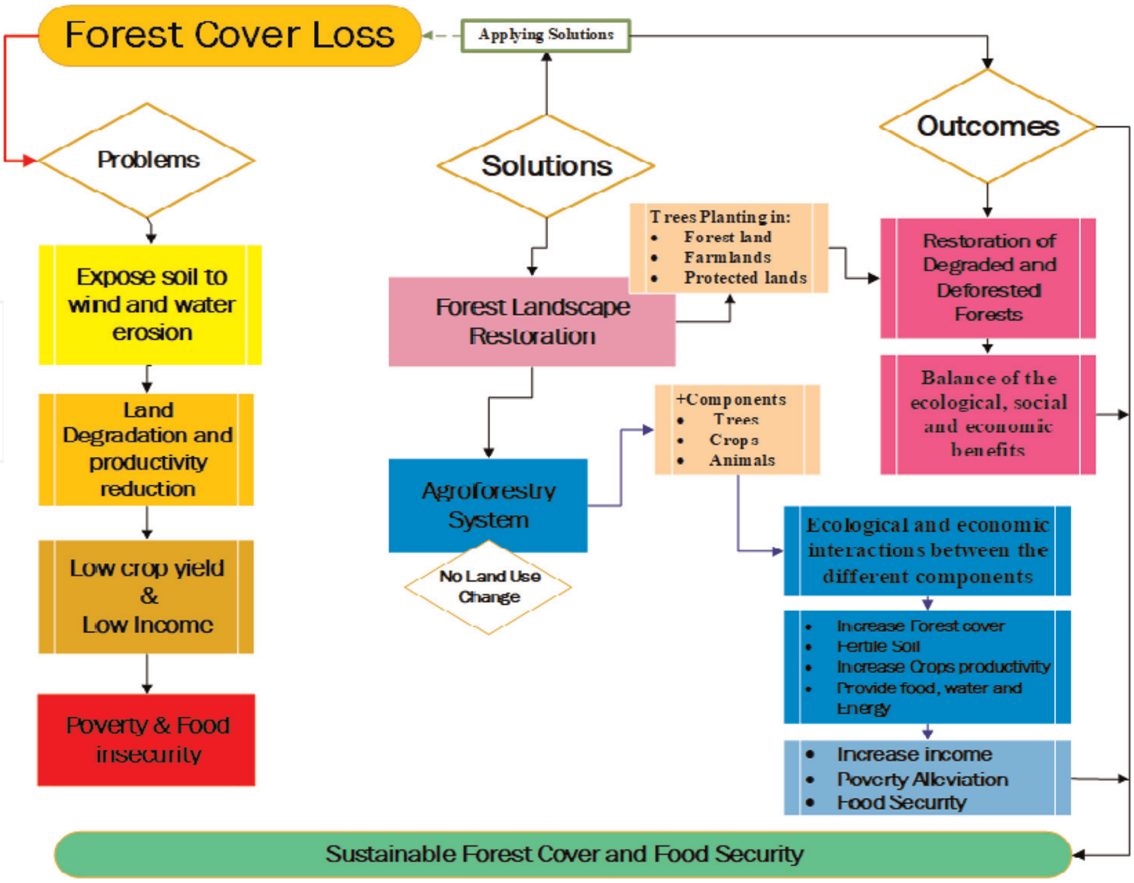

Figure 5.
Framework for Sudan forest landscape restoration [17].

well as potential restoration responses and their outcomes. The framework begins by identifying the root causes of degradation, which can be both natural and anthropogenic, and traces these to their immediate and long-term ecological and socio-economic consequences. It then outlines various restoration responses that could be applied, categorizing them into indirect approaches, such as policy changes or community engagement, and direct interventions like reforestation or soil stabilization. Finally, the framework emphasizes the necessity for robust monitoring and evaluation strategies to assess the effectiveness of these restoration efforts. This multidimensional approach aims to guide practitioners, policymakers, and researchers in the quest to address land degradation in a holistic manner.

Figure 5 outlines an Agroforestry System Framework tailored for the restoration of forest landscapes in Sudan. This comprehensive framework integrates agriculture, forestry, and local community needs to create a sustainable land management strategy. It begins with an assessment phase that gauges the current conditions of both agriculture and forestry sectors, identifying key issues such as soil degradation, deforestation, and community livelihood needs.

8. Conclusion

The urgent degradation of forest resources in Sudan's arid landscapes presents a complex, multi-layered crisis demanding swift and comprehensive action. This detailed review illustrates that the drivers of this degradation are varied and far-reaching, incorporating natural influences as well as human activities and policy-related decisions. The fallout of such degradation has ramifications beyond forest borders, impacting crucial areas like food security, biodiversity, land and water conservation, and also contributing to overarching global issues like climate change. To tackle this pressing dilemma, a dual-faceted strategy is indispensable. On one hand, immediate proactive steps must be taken to prevent the further decline of these vulnerable dryland forests. This includes a deep dive into the root causes, which span from unsustainable land management to policy shortfalls. Equally important is advocating for sustainable alternatives that carefully balance human developmental needs with ecological conservation. On the other hand, there's an urgent necessity for targeted efforts to rehabilitate already degraded forest landscapes and offset the consequent negative impacts. To ensure the efficacy of these interventions, it's critical to have a robust monitoring and evaluation mechanism in place. This system should be based on the five globally recognized indicators for assessing forest degradation, namely, biodiversity levels, productive functions, carbon storage capacities, overall forest health, and the forests' protective functions against erosion and other environmental stresses. With diligent, data-driven assessment and adaptive management, it's possible to turn the tide on these degrading trends and set Sudan's arid forests on a path toward resilience and sustainability. Given the monumental nature of the challenges at hand, collaboration emerges as a linchpin for success. It's essential to establish partnerships across local, national, and international platforms, where stakeholders can pool their collective knowledge, resources, and expertise. By working together, we can hope to not only preserve but also rejuvenate these invaluable dryland ecosystems. In doing so, we secure their essential contributions to human livelihoods, biodiversity, and overall environmental equilibrium, both within Sudan and on a global scale.

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