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Rehabilitation And Restoration Of Degraded Land Through Agroforestry: Mitigation Approaches And Future Prospects In India

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Abstract
Land degradation, driven by both natural and human activities, has a significant impact on forest land, resulting in losses in productivity, ecosystem functionality, and biodiversity. In India, it has become a pressing issue due to the growing population and excessive exploitation of natural resources. This phenomenon depletes soil quality, reduces agricultural and forest productivity, and poses a threat to biodiversity. Approximately 147.75 million hectares of Indian land are degraded, with contributing factors including water erosion (93.68 million hectares), acidification (16.03 million hectares), waterlogging (14.29 million hectares), wind erosion (9.48 million hectares), salinity (5.89 million hectares), and other causes such as ice caps and arid mountains (8.38 million hectares). Land degradation also exacerbates climate change. Soil erosion and deforestation are key outcomes of land degradation, reducing carbon sequestration and increasing greenhouse gas emissions through agricultural land expansion. Strategies like afforestation and reforestation are effective in combating deforestation and addressing land degradation. Agroforestry, in particular, plays a transformative role in mitigating land degradation by improving soil fertility, reducing erosion, and addressing salinity, alkalinity, and desertification. Agroforestry systems integrate diverse plant species, enhancing both ecological and socioeconomic conditions. Practices such as using Multi-Purpose Tree Species (MPTs), relay cropping, terracing, contour cultivation, strip cropping, and alley cropping offer sustainable solutions for low-resource farmers while restoring and improving land productivity. These methods contribute to stabilizing ecosystems, promoting biodiversity, and enhancing livelihoods.For agroforestry to effectively mitigate land degradation, active participation from farmers and local communities is crucial during planning, development, and implementation. By leveraging agroforestry's potential, sustainable land management can be achieved, addressing environmental and socio-economic challenges while supporting long-term agricultural productivity and ecosystem resilience.
Keywords: *Agroforestry, Climate change, Deforestation, Land degradation*

INTRODUCTION:

Land degradation is one of the significant global issues of the 21st century, causing deleterious impacts on the environment, agricultural productivity, food security, and all life forms on the earth (Eswaran et al., 2019). According to statistics, about 40% of the world's land has been degraded, threatening USD 44 trillion (UNCCD, 2022). Human attempts to achieve food, water, health, and development activities related to climate change will altogether create immense pressures, deepening land degradation further (Xie et al., 2020).

Land resources form the cornerstone of human survival and progress, providing essential material and spatial foundations for development. As a non-renewable resource, land's significance is immense (Sun et al., 2018;

Xie et al., 2020). However, escalating ecological degradation, burgeoning population pressures, rapid urbanization, and unchecked exploitation of natural resources have intensified land degradation, especially over the last century (Hammad and Tumeizi, 2012). Today, approximately 60% of the world's land area is considered degraded, presenting a formidable challenge to achieving sustainable land use (Pimentel, 2006).

Land degradation arises from a multitude of natural and anthropogenic factors, including deforestation, landslides, agricultural mismanagement, droughts, and extreme weather events. It diminishes soil fertility, accelerates salinity and alkalinity, and disrupts biodiversity, posing severe threats to ecological and economic stability (Van Engelen, 1997). The Food and Agriculture Organization (FAO) defines land degradation as the persistent decline in ecosystem function and productivity (UNEP, 2007). The scale of this crisis is vast, with approximately 75 billion tonnes of fertile soil lost annually due to erosion, resulting in an estimated global economic loss of $400 billion (Global Soil Partnership, 2017).

India, home to approximately 120.7 million hectares of degraded land (NAAS, 2010), is particularly vulnerable. Soil erosion caused by water (60.7%; 73.3 M ha) and wind (10.3%; 12.4 M ha) dominates the degradation processes, compounded by chemical and physical stressors such as salinity, alkalinity, acidity, waterlogging, and mining. Additional contributors include deforestation (2.07 M ha from 2001–2021), unregulated grazing (5.65 M ha), shifting cultivation (7.6 M ha), and indiscriminate fertilizer use (32 MT annually).

Climate change further exacerbates this challenge, introducing erratic rainfall, prolonged droughts, and extreme storms, which destabilize ecosystems and amplify degradation. Agricultural and forest ecosystems bear the brunt of these changes, resulting in increased pests, invasive species, food insecurity, and biodiversity loss (Lindner et al., 2010).Addressing land degradation necessitates integrated approaches such as forest regeneration and agroforestry. Agroforestry offers a sustainable solution, combining ecological restoration with socio-economic benefits. By integrating trees with crops and livestock, agroforestry combats soil erosion, restores fertility, and mitigates salinity, alkalinity, and desertification. Moreover, it enhances carbon sequestration, reduces greenhouse gas emissions, and buffers the effects of climate change (Verchot, 2008).

Agroforestry systems, ranging from silvopastoral practices and home gardens to tree-crop integration and biomass production, are tailored to diverse ecological and socio-economic contexts (Zomer et al., 2009). They enhance biodiversity, strengthen ecosystem resilience, and provide multifunctional benefits such as timber, fodder, and food. These systems reduce vulnerabilities to climate risks while fostering sustainability, making them invaluable tools for managing degraded lands and mitigating climate change (Zölch et al., 2016).By adopting agroforestry, communities can achieve a harmonious balance between land productivity, environmental health, and socio-economic development, paving the way for a resilient and sustainable future.

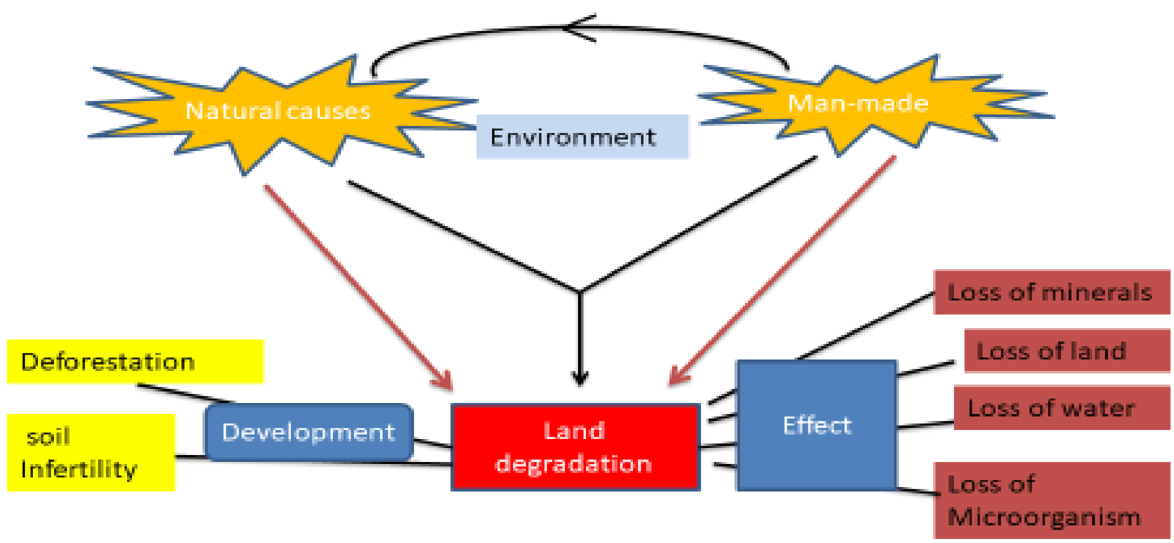


Fig.1: Causes of land degradation and their effect on the environment

Land Degradation Scenario of India

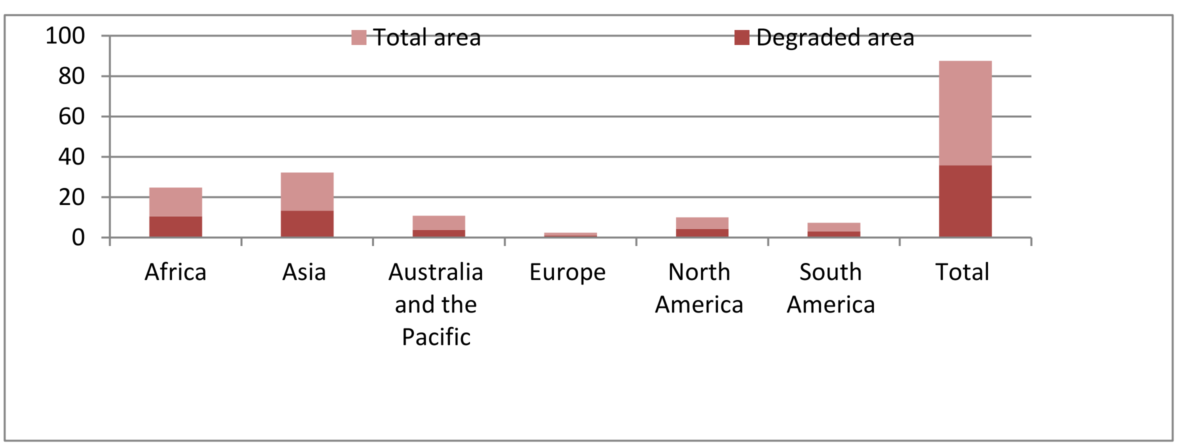
With a land area of 328.72 million hectares (Census of India, 2011), India ranks seventh in the world, second in arable land area at 1.55 billion hectares (World Bank, 2023), and first in livestock population at 536.76 million (Census Livestock, 2019). Deforestation, overexploitation, inappropriate agricultural practices, climate change, an increasing human population, erosion, and urbanization contribute to converting productive land into desert or drought-stricken land in the country. According to remote sensing and GIS database analysis, land degradation and desertification affected 97.85 million hectares (29.77%) and 83.69 million hectares of the country, respectively, in 2018-19. Water erosion, vegetation degradation, and wind erosion account for 11.01, 9.15, and 5.46% of desertification and land degradation for the same timeframe. Rajasthan, followed by Maharashtra, Gujarat, Karnataka, Ladakh, Jharkhand, Odisha, Madhya Pradesh, and Telangana with 23.79%, whereas the remaining states contribute less than 1% to land degradation and desertification in the country. States like Jharkhand, Rajasthan, Gujarat, Delhi, and Goa exhibited more than 50%, whereas Kerala, Assam, Mizoram, Arunachal Pradesh, Bihar, Haryana, Uttar Pradesh, and Punjab showed less than 10% area under desertification and land degradation (DLD) during 2018- 19 (SAC, 2021).

Land degradation affects globally

Land degradation presents a profound challenge, particularly for rural communities and farmers, with an estimated 3.2 billion people worldwide feeling its effects. As the global population continues to rise and is expected to hit around 9.7 billion by 2050, the demand for food, fuel, fiber, dairy, and animal feed will surge, intensifying pressure on already degraded lands. To address this, various agronomic, mechanical, and biological methods offer potential solutions for rehabilitating these compromised fields (Chaturvedi et al., 2018; Jinger and Kakade, 2019; Kumar et al., 2020).

Contributing to this issue are factors such as climate change-induced temperature fluctuations, extreme weather events, and deforestation for agricultural expansion, all of which exacerbate the strain on land resources and contribute to the ongoing loss of biodiversity (UNDP 2015). The most severe cases of land degradation occur in dryland regions, which cover roughly 40% of the Earth's land area. These areas are home to about two billion people, mainly in developing nations, where the impacts of climate change further challenge farmers, leading to diminished crop yields, lower incomes, weakened agroecosystem resilience, and reduced food security.

Globally, land degradation is most acute in Asia, followed by Africa, while Europe faces comparatively less severe impacts. According to the United Nations Development Programme (UNDP), around $42 billion in income is lost annually, and 6 million hectares of productive land are degraded each year. In Africa, the situation is especially dire, with erosion, deforestation, dust storms, and drought further depleting the land's productivity, which in turn fosters poverty and fuels migration (WMO, 2005). The issue of desertification affects over a hundred countries, encroaching on roughly 33% of the Earth's land surface, impacting around 2.6 billion people globally (Adams and Eswaran, 2000). The detailed degraded lands in dry areas, as per the continents, have been given in Table 1.



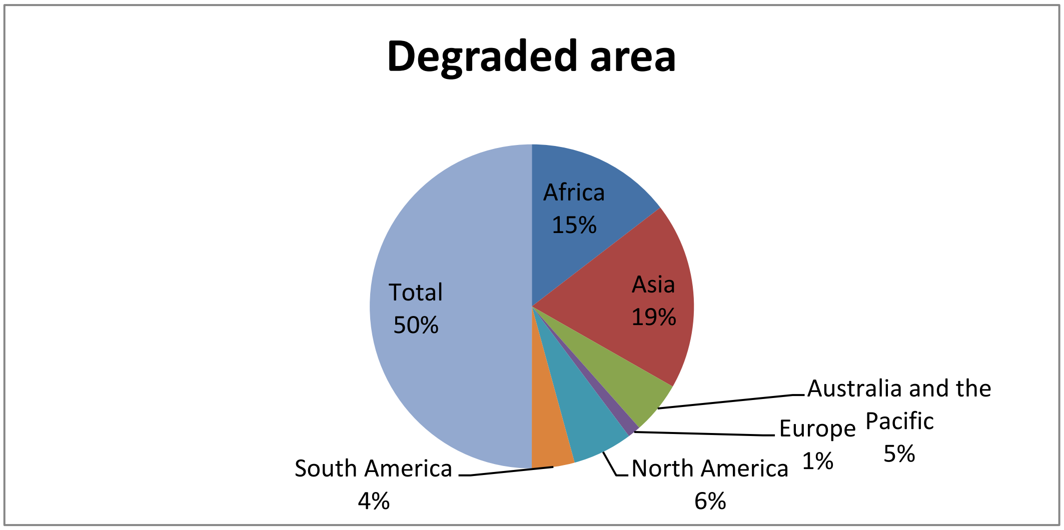


Fig.2: Total area, degraded area, and percentile under land degradation

Table 1: Extent of land degradation in India as assessed by different agencies

Organization	**A measurement year**	**Degraded area**	**Reference**
National Commission on Agriculture, New Delhi	1976	148.1	NCA, 1976
Ministry of Agriculture-soil and water conservation division, New Delhi	1978	175.0	MoA, 1978
Department of Environment, New Delhi	1980	95.0	Vohra, B.B. 1980
National Wasteland Development Board, New Delhi	1985	123.0	NWDB, 1985
Society for the Promotion of Wastelands Development, New Delhi	1984	129.6	Bhumbla, D.R.; Khare, A. 1984
National Remote Sensing Agency, Balanagar, Hyderabad	2000	53.3	NRSA, 2000
Ministry of Agriculture, New Delhi(20th ed.)	1985	173.6	MoA, 1985
Ministry of Agriculture, New Delhi(25th ed.)	1994	107.4	MoA, 1994
NBSS &LUP	1994	187.7	NBSS&LUP, 1994
NBSS & LUP (revised)	2004	146.8	NBSS&LUP, 1994
National Remote Sensing Agency, Balanagar, Hyderabad	2006	47.22	NRSA, 2006
ICAR, New Delhi	2010	120.4	Mandal, D ET AL., 2010

Major Cause of Land Degradation

Both natural and human-driven factors play a critical role in the widespread issue of land degradation. Natural events such as storms, volcanic eruptions, earthquakes, droughts, floods, tsunamis, wildfires, and tornadoes can all contribute to the degradation of land (Reynolds, 2001). These occurrences alter soil properties and disrupt ecosystem functions, with rainfall frequency and intensity being key factors in their impact (Sklenicka, 2016). While these natural forces are beyond human control, they still significantly affect land quality and sustainability.

In contrast, human activities are major contributors to land degradation, with practices like deforestation, overgrazing by livestock, improper irrigation, urbanization, and industrialization intensifying the problem. Unlike natural causes, human-driven factors can be managed and mitigated through more sustainable practices. Human actions such as greenhouse gas emissions, excessive resource extraction, and poor land management not only accelerate climate change but also exacerbate land degradation (Barrow, 1991).
Managing land degradation caused by human activities is a crucial step toward safeguarding our environment. Deforestation, industrial development, excessive mining, and off-road vehicle use are key contributors, as are the vulnerabilities of certain land types, like coastal and low-lying areas (Reynolds 2007; Salvati and Zitti, 2009). The impacts of land degradation are far-reaching, resulting in reduced crop yields, declining soil fertility, depletion of natural resources, and the loss of biodiversity—factors that directly contribute to food insecurity and economic instability.However, there is hope. Land degradation can be reversed through reclamation efforts, which involve rehabilitating degraded lands to restore their productivity. This process aims to transform these areas into valuable, sustainable resources that can once again meet human needs.

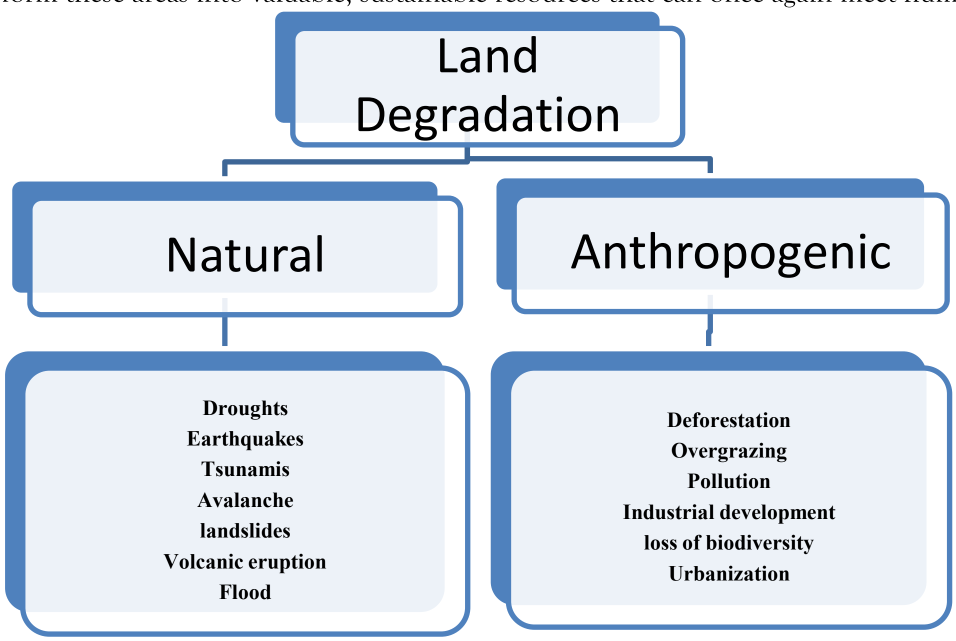


Figure 3: Land degradation causes

Natural causes of land degradation

Land degradation arises from two primary types of causes: direct and indirect. Direct causes stem from human activities that directly disturb the land, while indirect causes are more complex and include broader factors such as land policies, international trade regulations, poverty, land tenure issues, population pressure, and the availability of agricultural extension services (AbdelRahman et al., 2022). A major direct cause of land degradation is deforestation, which threatens community survival. This occurs when natural resources like wood for fuel, livestock grazing, and agricultural expansion are overused, leading to significant damage to the land. Similarly, soil degradation results from the excessive extraction of resources, further undermining land productivity.
Natural forces also contribute to land degradation. Events such as tsunamis, earthquakes, floods, droughts, and volcanic eruptions can significantly impact the land. Research has shown that earthquakes, for instance, have historically led to land degradation. In the 2004 earthquake in Sumatra, Indonesia, and the 2008 earthquake in Sichuan, China, vast areas of land were damaged. In Sichuan, around 400,000 hectares of rice fields were destroyed, and the soil texture shifted from sandy to silty clay loam as a result of the seismic activity (Gang, 2008; Hulugalle et al., 2009).
Droughts, while occurring naturally, can have varying impacts based on social characteristics. Even if the drought's intensity and duration are consistent, the effects can differ from one region to another due to social and economic factors (Aboelsoud et al., 2022). During droughts, topsoil dries out and becomes more prone

to erosion by wind and rain. Since the topsoil is the most fertile layer, its depletion significantly hampers crop production, further aggravating the challenges to agricultural productivity (Singh et al., 2000; Zhao et al., 2008).

Human-induced causes

Human activities play a crucial role in both directly and indirectly driving land degradation. Direct causes of land degradation include practices such as deforestation, industrialization, urban expansion, mining, overgrazing by livestock, and improper agricultural management, particularly irrigation (Janečková et al., 2023). These actions lead to the destruction of vital land resources and result in reduced land productivity (Mohamed et al., 2019).

Indirectly, the ever-growing human population—exceeding the capacity to meet food demands—has led to unsustainable agricultural practices. This growing pressure on resources accelerates land degradation as more intensive farming methods are adopted. For example, between 1975 and 1990, around 220 million hectares of tropical forests were degraded due to the relentless pursuit of food production (UNDP 2004). These trends underscore the complex link between human population growth and the degradation of natural landscapes.

Deforestation

Deforestation, the widespread loss of trees, is driven by a combination of human and natural factors, though the human impact remains the most alarming. Human activities such as population growth, urbanization, industrialization, commercial development, and agricultural expansion are major contributors to the daily destruction of forests. In certain regions of India, shifting cultivation practices exacerbate deforestation. According to the Food and Agriculture Organization (FAO), approximately 13 million hectares of forest are lost annually (Kaimowitzand Angelsen, 1988).Deforestation has far-reaching environmental consequences. It accelerates salinization by increasing soil water loss, which creates a drier atmosphere and leads to reduced rainfall. This disruption not only diminishes biodiversity but also contributes to the drying up of rivers. Forests play a vital role in maintaining soil stability by binding the soil and aggregating soil particles through their root systems. When forests are removed, this natural process is disrupted, resulting in soil erosion, declining soil fertility, and reduced agricultural productivity.

The FAO's 2015 Forest Resources Assessment (FRA) (FAO 2016), reviewed by Keenan et al. (2015) and Sloan and Sayer (2015), indicates a global decline in forest areas, with a 2.8% reduction between 1990 and 2010 (D'Annunzio et al., 2017; Lindquist and D'Annunzio, 2016). The total global forest area is estimated to have dropped by 3% from 1990 to 2015. However, there is a discrepancy in the trend of deforestation between different assessments. While remote-sensing data suggests a slowdown in deforestation, the FAO (2016) reports that the rate of loss is accelerating. Between 2010 and 2015, tropical forests alone lost about 55,000 km^2 annually. The FRA notes that from 1990 to 2015, the global natural forest area shrank from 39.61 million km^2 to 37.21 million km^2 (Keenan et al., 2015).

Overgrazing

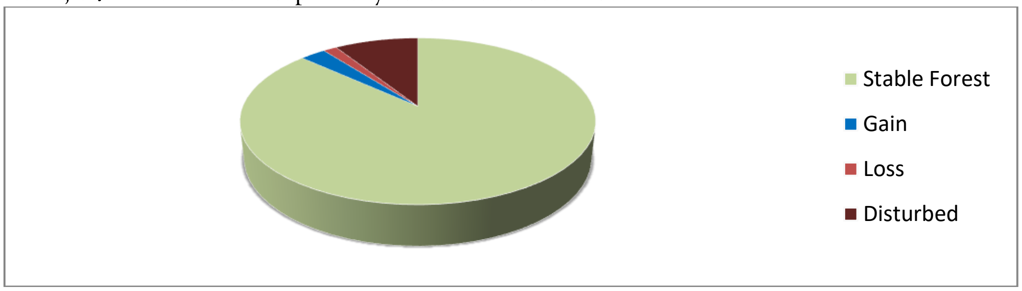
Overgrazing of grasslands has significant negative effects on soil health, leading to reduced fertility and increased erosion of the topsoil. The excessive grazing of livestock causes soil compaction, which impairs the soil's ability to absorb water, reducing its infiltration capacity. With livestock populations surpassing the available grazing area, which continues to shrink, the resulting overgrazing hinders plant recovery by limiting regrowth time. Additionally, the activity of soil microorganisms, which are essential for maintaining soil fertility, is diminished. This disruption can lead to increased concentrations of nitrate-N and ammonium-N, substances that can be toxic to plant roots (Czegledi and Radacsi, 2005).

Research has shown that sustainable grazing practices can help preserve plant cover, which in turn reduces runoff, sediment yield, and soil water loss due to evapotranspiration (Carmona et al., 2013). Studies across various environmental contexts have confirmed the critical role of plant cover in controlling water runoff and sediment loss (Dunjo et al., 2004; Marques et al., 2007). Sustainable grazing is also an effective management strategy for preventing soil erosion on grazing lands (Bernue et al., 2011). Notably, sustainable grazing practices have been shown to result in lower rates of soil erosion compared to overgrazing, particularly during periods of heavy rainfall (Gomez et al., 2009).

Overgrazing, on the other hand, leads to changes in soil chemical properties and a decline in fertility. Excessive grazing pressure negatively affects plant productivity and leads to a reduction in soil organic matter (SOM) (Conant and Paustian, 2002). The loss of vegetation biomass and canopy cover due to overgrazing contributes to reduced SOM and overall soil fertility. Furthermore, visible signs of soil degradation, such as compaction of the topsoil by livestock, are particularly evident in areas with steep slopes and near livestock shelters used by nomadic communities.

Human Causes of Deforestation:

According to the Global Forest Watch Report,in 2010, 31.3 Mhaof natural forest occurred over 11 % of land area in India; however, in 2021, due to deforestation, it decreased by about 127 Km/ha.From 2002 to 2021, 371 kha of humid primary forest have been lost in India.



***Source: Global Forest Watch**

Figure 4: Component of net change cover in India

Population growth:

Population growth is a serious concern worldwide and is a major reason for land degradation (Gang H., 2008). It has been observed that population growth has a relationship with agricultural development, infrastructure development, and growth rate. Globally, the increasing population is an alarming situation at present. The Population Reference Bureau reported a world population of 6.14 billion and an estimated population of 1.033 billion in India in 2001. The population of the country has increased by 1.26 billion as of 2016. In recent years, land redistribution has become a major issue due to the acquisition of lands for new households, resulting in land fragmentation and a reduction of cropland. Land fragmentation leads to a decrease in cropland per capita, which in turn reduces the planting of trees and the following activities. These factors ultimately result in reduced crop yields and create food insecurity (Hulugalle, 2009).

Farming System: A farming system is a farming practice in which farmers cultivate crops integrated with different interacting farm enterprises to efficiently and properly use land, time, and labor, providing yearly income to farmers and their families. This method is highly beneficial for improving the socio-economic conditions of farmers. However, some drawbacks have been observed regarding land degradation. Farmers often practice these farming systems without proper knowledge and understanding of the relationship between crops and soil, which can degrade soil quality through water loss and soil erosion. Furthermore, farmers who engage in these practices without considering soil-water relationships and conservation measures contribute to soil degradation (Singh, 2000).

Impacts of Land Degradation

Aqueducts dry up, once lush meadows are now overgrown with prickly plants, gullies emerge on the ground, and the soil becomes hard and rocky, among other signs of land degradation. These issues have a significant impact on the environment, affecting the lives of all organisms that depend on it (Zhao, 2008).

Climate change

Due to its direct or indirect effects on living things, climate change is a significant issue in the current situation. These climatic changes have a huge impact on the land. Globally, about 136+55 GT of carbon emissions to the atmosphere have been observed since the Industrial Revolution (Anonymous, 2000). Due to changes in the uses of soil, the soil organic pool has been depleted by approximately 78 ± 12 GT. Vegetation is dependent on temperature, precipitation, and other climatic conditions; if any of these factors change, it can affect the vegetation population. If rainfall is low, it decreases vegetation. Organic matter production in soil decreases due to high temperatures, low precipitation, and rapid oxidation. High temperatures and low precipitation lead to low organic matter production in soil and rapid oxidation, leading to low aggregation and making it vulnerable to erosion by wind and water. In Africa, water erosion was found at 25%, wind erosion at 22%, and climate stress availability at 62.5% due to land degradation (Reich, 2001). Rainfall is one of the most viable factors, but excessive rainfall causes soil erosion, and lesser rainfall affects desertification, so we can say that excessive or lesser rainfall can cause land degradation. In this sequence, other climatic factors like floods and droughts also cause land degradation (WMO, 2005).

Socio-Economic Consequences of Land Degradation

In many regions, particularly in Asia, Africa, and Latin America, food insecurity is closely linked to land and water degradation, which exacerbates poverty and weakens ecosystem resilience (Chomitz et al., 2007). The degradation of land significantly contributes to environmental decline, negatively impacting both human and animal health and undermining livelihoods. For instance, in Africa, the economic consequences of land degradation are severe, further entrenching poverty (Project Development Facility, 2007). Soil and water erosion are major contributors to the depletion of natural resources, accelerating land degradation and leading to the loss of soil fertility, nutrients, water, and agrobiodiversity (UNDP, 2004; Anonymous, 2000).

Land degradation severely hampers agricultural productivity, contributing to food shortages and exacerbating poverty (IFPRI, 2005). Deforestation and erosion, in particular, contribute to land degradation, leading to additional challenges such as frost, drought, and other environmental factors that result in food shortages, as seen in Ethiopia (Lal, 2004).

Ecological Consequence

Land degradation is such a sensitive issue that it is having side effects both directly and indirectly on ecology and ecosystem functions and services. The environmental impacts of land degradation include heavy water flows, rapid loss of biodiversity and habitats, and sedimentation of coastal and other reservoirs (Project Development Facility, 2007). Ecological impacts of land degradation include loss of soil properties like chemical, physical, and/or biological, which directly and indirectly affect plant growth and development, depletion of aquifers, and decreased availability of potable water (Zhao et al., 2008). Land degradation is also responsible for affecting biodiversity resources and agricultural productivity (Reich et al., 2001).

Impacts of agricultural activities on the degradation of land

Soil nutrient depletion

Soil erosion leads to the removal of very important nutrients like potassium, nitrogen, calcium, and phosphorus, which are essential for plant growth. When the organic matter layer is depleted, crop productivity declines because the soil structure degrades and nutrients are depleted, which are available in organic matter (Kaimowitz and Angelsen, 1988).

Lessening the Crop Production

The decline in organic matter in soil makes the soil quality poor due to soil erosion and decreases the productivity of biomass in ecosystems. This eventually has an intense effect on the plant, animal, and microbe diversity in ecosystems. The direct and indirect effects of erosion on ecosystems are frequently nearly as damaging as reducing plant productivity.

Recovery Methods for Land Degradation

Land degradation can be worked out and fended off in different ways, depending on its nature and the form of degradation. Various soil degradations can be turned aside through afforestation and reforestation methods, or buffering soil acidity, in eroded soil to add some important nutrients that improve soil fertility and increase soil productivity (FAO, 2005). Environmental factors are important to prevent land degradation and improve soil productivity, which can be recovered by expanding the vegetation cover and promoting intercropping and agroforestry systems, which reduce the risk of deforestation. However, UNCCD (2004) exposed that tree and forest cover reduce the impact of desertification and land degradation through soil stabilization, as well as maintaining the soil nutrient cycle and reducing wind and water erosion (WMO 2005).

Agroforestry can recover degraded land

Indian traditional agroforestry systems range from seemingly simple shifting cultivation to complex home gardens; from high-density multi-story homesteads of humid lowlands to sparse stands of trees on farmlands;

and from systems where trees are primarily used as a "service" to those where they are the main source of commercial goods. Most of them are anecdotal, but enough studies have been done recently on some of them (GOI, 2001; Pathak et al., 2006).

Table 2: Carbon sequestration and production potential under different agroforestry systems in different regions of India

S.No.	Agro-climatic zones	Agroforestry system	Carbon sequestration potential (Mg C ha^{-1} $year^{-1}$)	Food production potential (Mg ha^{-1} $year^{-1}$)	References
1.	Western Himalayan Region	Agri-horticulture (Prunus armeniaca + Ocimum sanctum)	1.8 0	11.0 (Apricot) 1.90 (Tulsi)	Handa et al. (2020)
2.	Trans-Gangetic plains Region	Agri-silviculture Populus deltoides + wheat/potato/turmeric	9.12	3.26 (Wheat) 13.1 (Potato) 9.1 (turmeric)	Chavan et al. (2022)
3.	Lower Gangetic Plains Region	Agri-silviculture (Eucalyptus tereticornis + wheat)	8.6	3.0 (Wheat)	Bisht et., 2022
4.	Western Plateau & Hills Region	Agri-silviculture (Ailanthus excelsa + cowpea-mustard)	9.6 4	0.47 (cowpea) 0.75 (mustard)	Handa et al. (2019, 2020)
5.	Southern Plateau and Hills Region	Silvipasture system (Leucaena leucocephala + Gliricidia sepium)	23.2	9.20 (Leucaena) 18.5 (Gliricidia) 5.84 (Grass)	Handa et al. (2019)
6.	Gujarat Plains & Hills Regions	Silvo-aromatic (Melia dubia + lemon grass)	20–25	11 (lemon grass)	Jinger et al. (2022c)
7.	Western Dry Region	Silvipasture system (Ailanthus + Cenchrus ciliaris/Panicum antidotale)	9.64	5–6 (Fodder)	Handa et al. (2020)
8.	Central Plateau & Hill Region	Agri-silviculture (Acacia + greengram-mustard)	3.70	0.75 (Greengram) 1.3 (Mustard)	Newaj et al. (2008)
9.	West Coast Plains & Ghats Region	Agri-silvi-horticulture (Artocarpus heterophyllus + Acacia auriculiformis)	9.90	30 (Jack fruit)	Kunhamu et al. (2012)

As agroforestry stores atmospheric carbon in its biomass and soil, it has enormous potential to lessen the effects of climate change. According to estimates by Murthy et al. (2013), the average amount of carbon absorbed by agroforestry practices varies by zone and is 9, 21, 50, and 63 Mg C ha^{-1}. By lowering the kinetic energy of raindrops, dense canopy spread in an agroforestry system lessens the intensity of rainfall. After that, water transfers extremely slowly from the soil to the tree-crop (agroforestry) system. As a result, there is less runoff velocity and more time for the soil to absorb the water. Reclaiming fallows, cultivable fallows, pastures, groves, and troublesome soils would be how India achieves its goal of 53 M hectares under agroforestry by 2050 (Dhyani and Handa, 2013).

The following section discusses the various agroforestry technologies for lands affected by chemical (saline, sodic, and acidic soils), physical (mining and industrial waste and waterlogged lands), biological (degraded lands due to SOM depletion, reduction in soil fauna, and emission of greenhouse gases (GHGs), and wind- and water-eroded soils.

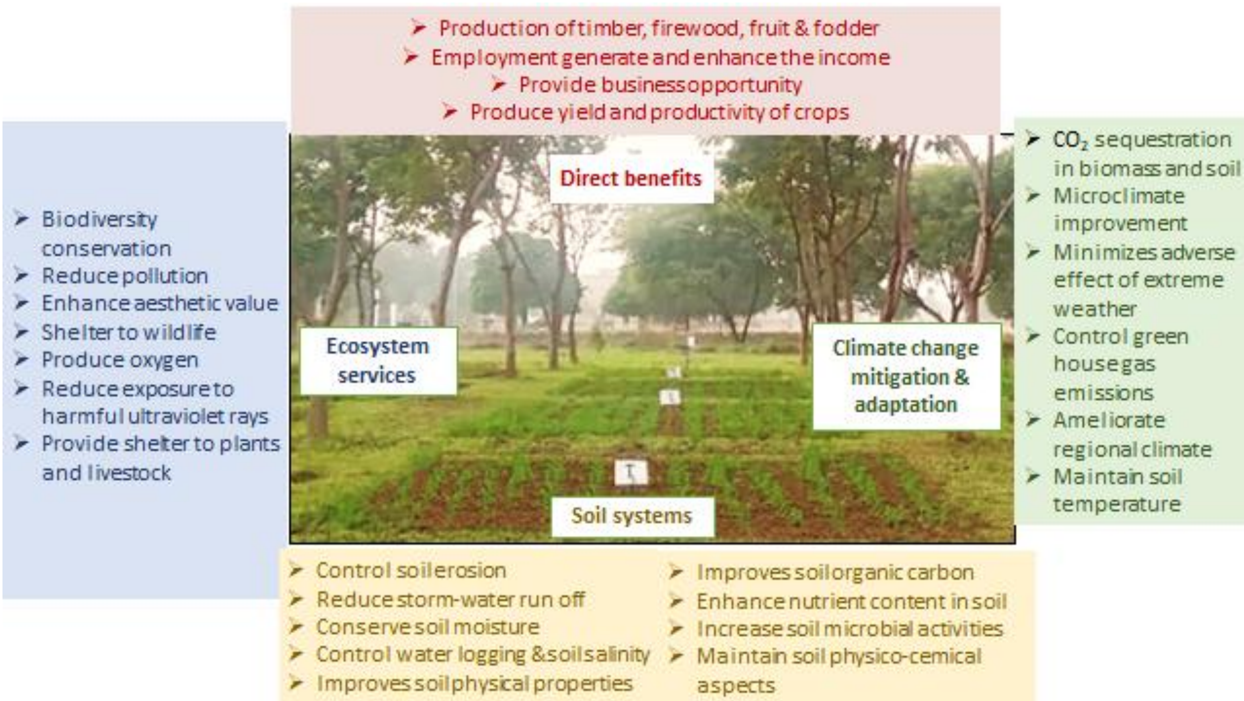


Figure 5: Degraded areas in direct and indirect impact of agroforestry

Water eroded land

Soil erosion caused by water is one of the primary causes of land deterioration. Approximately 68.4% (83 M ha) of India's total degraded land (120.7 M ha) is affected by water erosion, ranging from moderate (>10 Mg ha^{-1} year^{-1}) to highly severe (>80 Mg ha^{-1} year^{-1}). Water erosion is the primary threat that runoff water poses to the quality of the soil. The consequences include pesticide and heavy metal poisoning, loss of organic carbon, nitrogen imbalance, compaction, and a decline in soil biodiversity. Trees contribute to a decrease in soil erosion. Tree canopy in agroforestry primarily prevents soil erosion by absorbing rainwater, which lessens the force of raindrops and their potential to erode soil (Kaushal et al., 2017). By generating water-stable aggregates, litter contributes to the volume reduction of surface runoff. Water can seep through the roots and stems, which also prevent sediments from sliding down the slope (Zuazo and Pleguezuelo, 2008). Windbreaks and shelterbelts, hedgerow (alley) cropping, multilayer tree gardens, home gardens, plantation crop combinations, and multilayer tree gardens are the most often used agroforestry approaches for managing erosion (Young, 1997).

Deteriorated hillsides

In steeper terrain, landslides and other gravity erosion processes are more likely to happen. Because they have less plant cover than shorter, less steep slopes, longer, steeper slopes are more likely to erode after heavy rains. For water-eroded soils in the northwest and northeast Himalayan regions, a number of agroforestry models have been created and assessed (Kaushal et al., 2021a). Vegetative barriers consisting of hedgerows of trees like Leucaena and Gliricidia and grasses are the best filter strips to stop erosion and increase agricultural output in marginal regions. Hedgerows are highly useful in limiting the loss of organic carbon and nutrients during the erosion processes in a variety of land-use regimes. Soil and nutrients accumulated near the biological barrier system as a result of hedgerow obstruction. Lenka et al. (2012) state that grass filter strips and hedgerows (Indigofera) are excellent soil conservation tools since they can hold onto 43% of the soil's available nitrogen, 56% of its phosphorus, 54% of its potassium, and 48% of its soil organic carbon. Hombegowda et al. (2020) reported that the configuration of the land slope decreased by 0.41- and 0.27-degrees year^{-1}, respectively, under hedgerows based on Gliricidia and Leucaena, indicating the deposition of eroded soils on the lower slope side and the ensuing decrease in the land slope. Semicircular ditches with Dendrocalamus hamiltonii species can be an effective land restoration strategy on degraded sloping soils in the Himalayan foothills, claim Kaushal et al. (2021a).

Ravine and gully areas

Water erosion is a major problem in dry and semi-arid areas, causing gullies and ravines. The restoration of ravine lands requires the utilization of gullies by land capacity classes, conservation of soil and water, and permanent plant cover through afforestation or agroforestry systems (Chaturvedi et al., 2014). According to Soni et al. (2018), the recently planted trees mitigate soil and nutrient loss from these areas and offer risk mitigation against the unpredictability of agricultural output under the challenging conditions of ravine regions. The silvopastoral system is quite effective in the ravine region. According to Chaturvedi et al. (2011), a number of noteworthy grass species, such as Pennisetum purpureum, Brachiaria mutica, Cenchrus ciliaris, Cenchrus setigerus, Panicum antidotale, and Panicum maximum, are helpful for improving the supply of fodder in the ravine regions. On the top, slopes, and bottom of ravines, plantations of Acacia nilotica and Acacia tortilis with Cenchrus ciliaris yielded 28.7 Mg ha^{-1} and 27 Mg ha^{-1} of fuel wood, respectively, at a spacing of 3 m × 3 m. The mean annual pasturage yield under Acacia nilotica and Acacia tortilis varied from 1.52 Mg ha^{-1} year^{-1} to 2.06 Mg ha^{-1} year^{-1} (Kurothe et al., 2018).

Waterlogging

Waterlogging is caused by excessive rainfall, flooding, over-irrigation, or a high-water table. Due to intense and erratic rainfall brought on by climate change, waterlogging is now considered a dangerous abiotic stressor (IPCC, 2014). Studies have shown that systems based on fast-growing, short-rotation trees have the potential to function as bio-drains, preventing waterlogging in places that receive canal irrigation. The bio-drainage methods are both financially and environmentally advantageous. Block planting of Eucalyptus tereticornis and fast-growing tree species such as Eucalyptus spp. Arjun, Karanj, jamun, and Casuarina a suitable species for bio-drainage (Kapoor, 2001; Uthappa et al., 2015). Furthermore, Ram et al. (2011) noted that the 5-year-old E. tereticornis exhibited an average transpiration rate of 30.9 L Day^{-1} tree^{-1}, equivalent to 268 mm annually by 240 trees ha^{-1}.

Mined area

More than 20,000 known mineral resources are involved in the mining industry, which is crucial to the expansion of the Indian economy and creates the majority of the country's 5,60,000 new jobs per day (Ministry of Mines, 2018). Large volumes of waste from mining contain heavy metals, endangering agricultural soils, water sources, human health, and food supplies (Pulford et al., 2002). Trees may hold any amount of dirt by their roots to prevent erosion and percolation, or they can use their roots to pierce the stony layer, creating cracks that let surface water seep through. Azadirachta indica, Ricinus communis, Phoenix dactylifera, Psidium guajava, Butea frandosa, Leucaena leucocephala, and Artocarpus integrifolia were among the plants used in the mixed plantation, according to Ghosh (1991). The species chosen for rehabilitation should fix nitrogen, develop quickly, adapt well to arid environments, and exhibit drought-tolerant root architecture that has substantial socioeconomic value. Additionally, it contributes to the enhancement of soil microbial activity, which in turn promotes nutrient mineralization, subsoil biodiversity, nutrient cycling, and soil matrix stabilization. Based on his research, he discovered that Pongamia sp., Dalbergia sp., Albizia sp., and Azadirachta sp. species possess the greatest capacity to restore agro-ecosystems in areas that have been affected by mining (Datar et al., 2011).

Shifting cultivated area

India's eastern and northeastern regions engage in about 7.60 M hectares of jhum farming, or shifting agriculture (Bhat et al., 2022). According to Markose and Jayappa (2016), shifting farming is no longer sustainable due to the reduced jhum cycle caused by the strain of an increasing human population, significant soil erosion, low production, and loss of soil fertility. Lands were degraded by wind.

Wind erosion can be mild to severe in dry and semi-arid regions like the states of Gujarat, Punjab, Rajasthan, and Haryana. Furthermore, it is prevalent in the far northwest of India in both the frigid Leh (Jammu & Kashmir) desert regions and coastal places with mostly sandy soils (Singh et al., 2017; Singh et al., 2017). Policymakers and land managers are very concerned about wind erosion in drylands, which is one of the main factors contributing to land degradation and affects 33%–37% of the planet's continental areas (Sivakumar et al., 1998, and Duniway et al., 2019).

Carbon sequestration potential of agroforestry in India

Agroforestry can mitigate the atmospheric accumulation of greenhouse gases like CO_2, CH_4, CFC, etc. (IPCC 2000). Over the next 50 years, agroforestry systems will provide a way for the creation of synergies between adaptation and mitigation and have a specific mitigation potential of 1.1-2.2 PgC in terrestrial ecosystems (Solomon et al. 2007). Carbon sequestration potential in 2010 via 391,000 MgC yr^{-1} and in 2040 via 586,000 MgC yr^{-1}. Moreover, 630 million ha of unproductive croplands and grasslands were converted to agroforestry (Jose, 2009). In a land-use system deprived of trees, the expanse of carbon in the above-ground and below-ground biomass of an agroforestry system is usually much higher (Murthy et al., 2013). In Southeast Asia, under humid tropical lands, Agri silvicultural systems can store 12-228 MgC ha^{-1} and in dry lowlands, 68-81 MgC ha^{-1} (Murthy et al., 2013). The North American accompanying silvipastoral systems have the highest potential for carbon storage (90-198 MgC ha^{-1}). In tropical and temperate biomes, the potential for sequestering carbon in aboveground components of agroforestry systems is assessed to be 2.1 c 10 9 MgC yr^{-1} and 1.9 c 10 9 MgC yr^{-1} (Oelbermannet al., 2004). On carbon sequestration, agroforestry systems have unintended effects because, in natural forests, they reduce harvesting pressure, which is the prime sink for terrestrial carbon. They enhance carbon storage equally in trees and soil, thereby conserving soil characteristics. The Study of the effects of agroforestry practise on the soil carbon pool has specified a rate of rise of 2-3 Mg C ha^{-1} yr^{-1} (Garg, 1998). With a median value of 95 Mg ha^{-1} the carbon sequestration potential of tropical agroforestry systems is assessed to be 12-228 Mg ha^{-1} (Singh and Pandey, 2011). Further estimations recommend that throughout the following 50 years, 1.1-2.2 PgC could be stored in terrestrial ecosystems based on the global area suitable for agroforestry (585-1215 × 106 ha) (Albrecht and Kandji, 2003). In agroforestry systems across the world, the quantity of carbon stored ranges from 30 to 300 Mg ha^{-1} yr^{-1} to 1m depth in soil and from 0.29 to 15.21 Mg ha^{-1} yr^{-1} aboveground (Ramchandran et al., 2010). The growth and nature of the tree species affect the total carbon storage capacity of an agroforestry system, and vary from region to region (Newaj and Dhyani, 2008). In Indian agroforestry, the average carbon storage potential has been appraised to be 25 tC ha^{-1} over 96 million ha (Sathaye and Ravindranath, 1998). Substantial regional variability is associated with biomass production (Table 2). In Table 3, it is indicated that poplar, eucalyptus, and bamboo (species in the Bambuseae tribe) components have the highest rates in India. High carbon sequestration potential (16-36 Mgt ha-1 yr^{-1}) estimates mainly on tropical home gardens, (Koul et al. 2011) appraised that soil organic carbon (SOC) was highest (17.69 t / ha) in the natural forest of Shorea robusta Roth, tracked by pure plantations of Terminalia arjuna (Roxb.) at 13.29 t / ha Wight &Arn, Agri-horticulture and Agroforestry Systems are 12.14 t / ha, while pure plantations of tea (Camellia spp.), Dalbergia sissoo Roxb. have 0.66 t / ha. Followed by gardens (10.45 t / ha) and fallow land (10.05 t / ha), the lowest amount of SOC stock.

Table 3: In India, different agroforestry systems in the total storage of carbon

Area	Agri silviculture/silvipastoral/ Agri silvipastoral	Components	Total carbon storage (tC ha^{-1})	Reference
Semi-arid	Silvopastoral aged 5 yr.	Acacia nilotica + natural pasture	9.5-17.0	Rai et al. (2001)

		A. nilotica + established pasture	19.7	
		Dalbergia sissoo + natural pasture	12.4	
		Dalbergia sissoo+ established pasture	17.2	
		Hardwickia + natural pasture	16.2	
		Hardwickia binata established pasture	17.0	
	Agrisilviculture	Dendrocalamus hamiltonii	15.91	Kaushal et al. (2014)
Central India	Block plantation aged 6 yr	Emelinaarborea	24.1-31.1	Swamy et al. (2003)
Arid (Rajasthan)	Agrisilviculture aged 8 yr.	Emblicaofficinalis + Vignaradiata	12.7-13.0	Singh (2005)
		Hardwickiabinata + Vignaradiata	8.6-8.8	
		Colophospermum mopane + Vigna radiata	4.7-5.3	
Semi-arid	Agrisilviculture aged 11 yr.	Dalbergia sissoo+ crop	26.0	NRCAF (2006)
North-western Himalayas	Silvipasture		2.17	AICRPAF (2006)
	Agrihortipasture		1.15	
	Hortipasture		1.08	

Table 4: Net annual carbon sequestration by agroforestry components

Agroforestry components	Carbon sequestration (Mg $ha^{-1}.yr^{-1}$)
	8 (Populus spp.)
	6 (Eucalyptus spp.)
	6.51-8.95 (Bamboo spp.)
	16-36 (Tropical home gardens)

Source: Singh and Pandey (2011)

Systems of agroforestry for the security of livelihood

Agroforestry systems are crucial for addressing the needs of an expanding human and livestock population by increasing the productivity of the land. In rural places, it has the potential to be both protective and productive, creating job possibilities. Dhyani (2014) has emphasized the function of agroforestry in fulfilling the needs of low-income families and offering a foundation for improved and sustainable livelihoods in society.

The economy has benefited greatly from agroforestry's primary effects on employment and income generation, which are made possible by combining food crops (fruits, vegetables, legumes, pulses, citrus fruits, and edible medicines), economic crops, and other timber crops with a variety of uses and products. In a difficult time, trees in agroforestry systems help to food security and are a significant source of revenue. Multipurpose trees are crucial for traditional agroforestry systems that support rural food security and revenue creation. They also help to maintain social and cultural stability to some extent (Basu, 2014).

The role of agroforestry systems in mitigating and adapting to climate change
Carbon dioxide can be absorbed and stored by vegetation. It uses carbon from biomass in various parts of the system to help preserve climate stability. It depends on a variety of environmental elements, including terrain, wild species, the ecological system, and the density of the vegetation (Senpaseuth et al., 2009). Climate change will exacerbate the situation with regard to food security, as evidenced by declining yields, an increase in pest and disease outbreaks, and dramatic natural events like floods and droughts (Kaimowitz, 2003). Agroforestry has a unique potential function in reducing greenhouse gas emissions into the atmosphere (IPCC 2000).

Fertilizing pastures and crops it increases the amount of nitrogen in the soil. There are times when the intensity of N_2O emissions from soils increases and the soil CH_4 sink decreases (Mosier and Delgado, 1997). High nitrogen inputs and soil compaction are to blame for the decrease in the soil's capacity to absorb CH_4 (Palm et al., 2002). Wherever leguminous crops are managed to contribute nitrogen, there is insufficient data on the amounts of N_2O released or the effects on CH_4 consumption in agroforestry systems. By managing flooding and improving organic matter, irrigated rice lowers CH_4 emissions from fields (Wassman et al., 2000; Jain et al., 2000).

The largest contribution to preserving the resource base and fostering climate-resilient agriculture is being made by agroforestry systems (Dhyani and Handa, 2014). The foundation of a climate-resilient agricultural system is biodiversity (Swaminathan, 1983). Agroforestry systems may be able to assist farmers in adapting to climate change mitigation rather than carbon sequestration (Luedeling et al., 2011). A 20 percent reduction in xylem carbon storage results from the depletion of forest resources (Office of Environmental Policy and Planning, 2000).

CONCLUSION

Land degradation is a widespread issue that has a disastrous effect on the natural environment and sociocultural context of the majority of the world's nations. The main reasons include soil erosion, deforestation, and elimination of vegetative cover, fast population growth, imbalanced crop production, and overgrazing by livestock. Man has an impact on the variables that contribute to degradation processes, including topography, soil types, and age-ecological elements. The majority of history has focused on the construction of physical conservation buildings to stop or lessen land degradation, but, compared to vegetation-related conservation measures, these conservation measures have not done as much to minimize soil erosion or accumulate nutrients that have been withdrawn. However, as stated in the main text, there are a variety of approaches that can be used to prevent land degradation, depending on the type and extent of the degradation. Potential gives agroforestry the chance to create connections between land degradation management and initiatives to lessen climate change. to support vulnerable communities and conserve uncommon plant species as a means of adapting to the detrimental effects of climate change. Agroforestry practices support species richness and serve as evidence of biodiversity reservoirs deserving of further development and investigation. However, for optimum plant densities to be sustained in agroforestry systems,

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