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Carbon restoration in degraded and dryland systems

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Abstract

Carbon restoration in dryland and degraded ecosystems is uprising as a significant measure to combat climate change, improve soil health, and enhance resilience in the long run (Lal, 2004) ^[3]. Drylands, which make up almost 40% of the earth's land, are very vulnerable mainly because natural climate fluctuations, human activities, and irresponsible use of land lead to their deterioration (Reynolds *et al.* 2007) ^[7]. The absence of organic matter in soil will render a land infertile, thus incapable of supporting life of any kind. Also, the ongoing desertification will worsen with a massive decrease in fauna and flora (IPCC, 2019) ^[2]. Maintaining carbon in such soils means more than just global warming. According to FAO rural communities obtain their livelihoods from fishing and other fish related activities. However, the real situation is that many of these places look more like deserts. Carbon restoration is basically replenishing the soil and plants with more organic matter. This can be done through forestry agroforestry conservation agriculture, and regenerative grazing (Lal, 2020) ^[4]. Such approaches extract carbon from the atmosphere and release it to the soil where it remains. Microorganisms get reactivated. The total mass of biomass is increasing. Ultimately, soil disturbance is reduced (Paustian *et al.* 2016) ^[5]. But what about drylands? It is difficult. Rain occurs rarely. Evaporation is huge. The soil does not possess good stability. The producing ability of plants and organic matter length underground are limited by that (UNCCD, 2020) ^[8]. The use of traditional ecological knowledge to improve modern carbon restoration in drylands is encouraged in research (Reed *et al.*, 2015) ^[6]. Indigenous techniques for managing land for instance water harvesting and mixed cropping can rehabilitate degraded soils and enhance carbon stocks (FAO, 2017) ^[1]. In addition to this improvement, the monitoring and evaluation of carbon dynamics in these ecosystems has also improved as a result of remote sensing and geospatial technologies (IPCC, 2019) ^[2]. Although carbon restoration in drylands has potential and advantages, various socio-economic and environmental constraints are likely to impinge on its implementation. These constraints include land tenure issues, funding constraints and uncertainties around climate (Reynolds *et al.*, 2007). Dealing with these issues requires coordinated policy intervention, stakeholder participation, and a sustained long-term investment in best sustainable land management practice (UNCCD, 2020) ^[8].

Keywords: Carbon restoration, dryland ecosystems, soil organic carbon (soc), land degradation, carbon sequestration.

Introduction

Very little water is found in dryland ecosystems, which exposes these ecosystems to climate changes and human activities (Reynolds *et al.* 2007) ^[7]. The population density in those regions is over two billion and they utilize the land primarily in agriculture and animal rearing (UNCCD, 2020) ^[8]. In addition to cutting down of trees through over grazing, and absence of good farming practices causes soil desertification and depletion of soil organic carbon (Lal, 2004) ^[3]. The growth of population along with the alteration in the weather conditions trigger an upsurge in the land demand that the soil cannot support. This causes an acceleration in the weakening of preexisting strained regions (Reynolds *et al.* 2007) ^[7]. Poor soil has the result of reducing the productivity of crops. The direct outcomes are food insecurity and poverty (FAO, 2017) ^[1]. The fertility and composition of the soil depend to large extent on soil organic carbon. It contributes to nutrient transportation in the soil, water retention capacity of the soil and farm production (Paustian *et al.* 2016) ^[5]. It is currently also assisting in the creation of soil aggregates due to the fact that it aerates the soil and makes penetration of the root easy (Lal, 2004) ^[3]. De void farms are typified by reduced

outputs. It is caused by carbon dioxide in the atmosphere that brings about global warming (IPCC, 2019) ^[2]. Dry soils that do not have organic carbon do not retain moisture. As a result, droughts become more severe, and the process of infliction turns faster (FAO, 2017) ^[1]. The restoration of the carbon in soils has become an issue of primary interest in Climate policy and strategizing on environmental resilience. Carbon restoration is an act of improving the capability of soils and vegetation to store the carbon as a result of managing lands in a sustainable manner (Lal, 2020) ^[4]. It involves intensifying biomass supply, reducing disruption to the soil and enhancing the biological activity of the soil to stabilize organic matter (Paustian *et al.*, 2016) ^[5]. This process is especially critical in the dryland systems because of the vulnerable condition of these ecosystems and their exposure to desertification (UNCCD, 2020) ^[8]. Proper carbon restoration plans have the capacity to make soils more stable to climatic stressors, serve to improve water permeability, and make soils more resilient (Reed *et al.*, 2015) ^[6]. Also, the practices help to enhance the nutrient availability and soil fertility in the long term to sustain agricultural production in resource-limited contexts (Lal, 2020) ^[4]. Carbon restoration has gained global acceptance as

seen in international campaigns of raising global soil carbon reserves like the 4 per 1000 initiative that seeks to offset carbon emissions through raising soil carbon reserves (Lal, 2020) ^[4]. This project emphasizes the possibility of soils to serve as a large carbon sink that can compensate a large part of man-made greenhouse gas emissions (IPCC, 2019) ^[2]. Climate-smart farming and land-restoration work together to reverse desertification - this is a key part of UNCCD's strategy (UNCCD, 2020) ^[8]. For now, national programs pushing for these practices still rely on top-down mandates rather than local input (FAO, 2017) ^[1]. At least in theory, restoring degraded soils depends on science, policy, and people working side by side - Mostly when it comes to long-term carbon sequestration (Reed *et al.* 2015) ^[6]. A strong system needs both data and trust - without either, progress stalls. The process doesn't end with planting crops - soil health must be monitored over time.

Literature Review

Soil organic carbon dynamics

Organic carbon (SOC) of soil is an essential component of terrestrial ecosystem and its major determiner of the quality of soil, the productivity of the ecosystem and the regulation of the climate (Lal, 2004) ^[3]. It is the biggest carbon reservoir in terrestrial systems that surpasses the quantity of carbon kept in plants and the air combined (IPCC, 2019). ^[2] The SOC dynamics have a balance between the carbon inputs, mainly the plant residues and root biomass, and the carbon outputs which are the result of decomposition and mineralization processes (Paustian *et al.*, 2016) ^[5]. Environmental conditions like temperature, precipitation and soil moisture have a strong bearing on these processes, which acts as the regulators of microbial activities and organic matter transformation (Reynolds *et al.*, 2007) ^[7]. The SOC processes in dryland ecosystems are exceptionally complicated because rainfall patterns are limited and unpredictable, which limit the vegetation growth and diminish the input of organic matter (UNCCD, 2020) ^[8]. The temperatures in these areas tend to increase the rate of decomposition and hence result in the quick deterioration of the soil organic carbon (Lal, 2004) ^[3]. Also, the lack of vegetation cover exposes soils to wind and water erosions, which also leads to the further carbon depletion (FAO, 2017) ^[1]. Spatial variability of SOC is also considerable in drylands because the heterogeneous patterns of carbon distributions are formed due to the micro-topographical variation and vegetation patches (Reynolds *et al.*, 2007) ^[7]. Microbes' communities are crucial to SOC processes because they mediate the breakdown of organic substances and stabilize carbon within the soil aggregates (Paustian *et al.*, 2016) ^[5]. In arid regions microorganisms are commonly limited due to the lack of moisture, which means that the decomposition process occurs in bursts after the rainfall (UNCCD, 2020) ^[8]. These pulses may lead to a high carbon mineralization rate and carbon dioxide production into the atmosphere, which leads to changes in the total carbon balance of these eco systems (IPCC, 2019) ^[2]. Moreover, the mineral composition and the texture of soils have a strong influence on the stabilization of SOC since the clay soils are more likely to retain the organic matter by physical and chemical processes (Lal, 2004) ^[3]. On the

contrary, sandy soils (that are prevalent in most dryland areas) are less able to retain organic carbon because of poor aggregation and a low level of nutrient availability (FAO, 2017) ^[1]. Thus, climatic, biological, and edaphic interactions cannot be neglected to predict the dynamics of the SOC and establish a combination of efficient carbon restoration plans in the drylands (Paustian *et al.*, 2016) ^[5].

Land Degradation and Carbon Loss

One of the most notable threats to the carbon stocks in the soil is land degradation, especially in drylands where the environment is already restricting the strength of the ecosystem (UNCCD, 2020) ^[8]. It also includes various processes such as soil erosion, salinization, nutrient loss, and loss of vegetation which lead to lessening of soil organic carbon (FAO, 2017) ^[1]. Due to the loss of vegetation cover, the amount of organic matter deposited to the soil is cut short, and there is much erosion of wind and water washing away physical topsoil containing carbon (Reynolds *et al.*, 2007) ^[7]. Deforestation, overgrazing, and unfriendly agricultural activities are anthropogenic activities that contribute significantly to the degradation of the land and loss of carbon (Lal, 2004) ^[3]. Examples of such include intensive tillage, which interferes with the structure of the soil and increases the initial oxidation of organic substances, resulting in the rapid loss of carbon (Paustian *et al.*, 2016) ^[5]. In the same manner, overgrazing also depletes biomass and roots of the plants, restricting the carbon supply and exposing soil to soil erosion (FAO, 2017) ^[1]. These mechanisms do not only reduce soil fertility but also promote the emissions of greenhouse gases, which makes land degradation connected to the global climate change (IPCC, 2019) ^[2]. It has been found out that degraded soils may lose up to 50 to 75 percent of their original SOC content, depending on the degree and length of degradation (Lal, 2004) ^[3]. Such loss is a huge amount of carbon released into the air and contributing to global warming as well as decreasing the ability of soils to serve as the carbon sink (IPCC, 2019) ^[2]. Additionally, the loss of SOC has a negative effect on the soil structure, the retention, and the nutrient availability that leads to the formation of a feedback loop that subsequently enhances the increase of degradation (Paustian *et al.*, 2016) ^[5]. Climate change is also the cause of land-degradation as it alters the frequency of precipitation and the occurrence of extreme weather situations i.e. droughts and heat waves (IPCC, 2019) ^[2]. These changes can reduce vegetation cover, as well as increase soil erosion, which will trigger a rise in carbon loss (UNCCD, 2020) ^[8]. Such climatic effects can pose a big restraint to the possible natural recovery of the degraded lands in dry land areas which is already constrained by the lack of water (Reynolds *et al.*, 2007) ^[7]. Thus, land degradation is a key problem that needs to be addressed to restore carbon stocks and increase the resilience of the dryland ecosystems (FAO, 2017) ^[1].

Restoration Practices in Drylands

The restoration of degraded dryland ecosystems is concerned with restoration of soil organic carbon by using sustainable land management practices which increase the vegetation cover and soil health (Lal, 2020) ^[4]. Agroforestry has been one of these practices which have received considerable attention because of its capacity to combine

trees with crops and livestock, which results in a higher biomass production and carbon capture (FAO, 2017) ^[1]. Trees also help in the input of carbon in the form of leaf litter and root biomass, as well as in enhancing micro climatic condition and soil fertility (Reed *et al.*, 2015) ^[6]. Another commonly popular practice is conservation agriculture, which focuses on the minimal disturbance of the soil, its long-term cover with grass and various crops (Paustian *et al.*, 2016) ^[5]. Conservation agriculture improves the soil structure, decreases erosion, and augments the level of organic matter by lowered tillage and keeping residues of crops on the ground (Lal, 2020) ^[4]. Such practices are especially useful in dryland systems because they enhance the penetration of water and decrease the rates of evaporation, thus facilitating the growth of plants and storage of carbon (FAO, 2017) ^[1]. Relevant efforts are also taken to ensure that the carbon stocks of degraded lands are restored through the help of reforestation and afforestation (IPCC, 2019) ^[2]. Such activities include the planting of trees in the deforested and barren areas, which maximizes the

carbon sequestration above the ground and below the ground (Lal, 2020) ^[4]. Nevertheless, they can be victorious in drylands, yet this will be achieved through the choice of drought-tolerant species and the adoption of proper water management techniques (UNCCD, 2020) ^[8]. Besides these methods, regenerative grazing has been developed to be a viable solution towards restoring the soil carbon in the rangeland ecosystems (Reynolds *et al.*, 2007) ^[7]. Regenerative grazing helps to regenerate plants and stimulate soil organic matter supply by controlling the movement of livestock and grazing pressure (FAO, 2017) ^[1]. This is not only effective in enhancing the health of the soil but also in sustainable production of livestock in the drylands (UNCCD, 2020) ^[8]. E novel technologies like remote sensing and geographic information systems (GIS) have ensured that monitoring and evaluation of carbon restoration efforts is enhanced (IPCC, 2019) ^[2]. These instruments allow tracing carbon stocks in the soil, determining the degraded zones, and measuring the result of restoration in broad spatial dimensions (FAO, 2017) ^[1].

Parameter	Description	Impact on Carbon Restoration
Rainfall	Low and erratic precipitation	Limits vegetation growth and carbon input
Temperature	High temperatures	Accelerates decomposition of organic matter
Soil Type	Sandy, low fertility soils	Poor carbon retention capacity
Vegetation Cover	Sparse and patchy	Reduced biomass input to soil
Evaporation Rate	High	Decreases soil moisture availability

Methodologies

The utilization of carbon restoration methods in drylands is primarily focused on the better management of the soil and its vegetation cover in order to improve the stocks of organic carbon (SOC) in the soil and enhance its resilience (Lal, 2020) ^[4]. These strategies will lead to the achievement of the balance between carbon inputs and outputs through sustainable land-use management that will reduce the process of degradation and increase the process of carbon sequestration (Paustian *et al.*, 2016) ^[5]. Dryland ecosystems are fragile, and the effective approaches are to be adapted to the local climatic environment, soil types, and socio-economic conditions (UNCCD, 2020) ^[8]. One of the most prevalent approaches in terms of carbon restoration is conservation agriculture that revolves around the topic of minimal disturbance of the soil, soil permanently covered, and diversified systems of crops (FAO, 2017) ^[1]. The amount of tilling to be done is also less or Non-existent which is useful in conserving the soil structure and reduces the oxidation of organic matter therefore retaining soil carbon (Lal, 2004) ^[3]. Crop rotation and intercropping is done to enhance the soil fertility through the improvement of nutrient cycle and the amount of biomass that is added to the soil (Paustian *et al.*, 2016) ^[5]. Furthermore, the residual crops that are present on the surface of the soil provide a shield against soil erosion, reduce the loss of moisture, and provide an endless source or supply of organic elements to microorganisms (FAO, 2017) ^[1]. The practices also come in handy in dryland systems which are largely prone to drought conditions due to their efficiency in water use and reducing their susceptibility to drought conditions (Reynolds *et al.*, 2007) ^[7]. Another significant methodology is agro forestry, which combines trees, crops, and animals to create multi-purpose

sceneries with the potential to store large amounts of carbon (Reed *et al.*, 2015) ^[6]. Trees aid in trapping carbon as they store organic matter in the roots of deeper soils and above ground biomass, which can be seen as carbon storage (Lal, 2020) ^[4]. Trees also help to improve the microclimatic conditions by providing shades and, consequently, decrease the pace of the wind and increase the degree of soil moisture retention (FAO, 2017) ^[1]. In addition, the agroforestry systems promote recycling of nutrient and biodiversity, which in its turn sustain the soil health and its productivity in the long run (Paustian *et al.*, 2016) ^[5]. In dryland areas, tree species that withstand drought are also often chosen in order to provide an opportunity to survive and further inject carbon in the water-restricted environment (UNCCD, 2020) ^[8]. The regenerative grazing has been increasingly picking up as an option of restoring carbon in the ecologies of the rangelands (Reynolds *et al.*, 2007) ^[7]. This method involves the strategic management of the grazing livestock to simulate the natural grazing systems so that the vegetation can regenerate and offer an everlasting cover to the ground (FAO, 2017) ^[1]. Controlled grazing enhances production of root mass and plant growth that increase the supply of organic carbon to the soil (UNCCD, 2020) ^[8]. Moreover, the growth of the root and organic matter will result in the enhancement of the soil structure that will enhance water penetration and reduce erosion (Lal, 2020) ^[4]. Properly conducted regenerative grazing may assist in transforming bad rangelands into functional ecosystems which are more capable of storage of carbon (Paustian *et al.*, 2016) ^[5]. Other mainstream practices of the restoration of carbon in degraded drylands are reforestation and afforestation that is moderated by the species used and practices (IPCC, 2019) ^[2]. Native and drought-resistant trees types are more effective in the carbon sequestration process and their

planting may significantly improve the soil resistance to erosion as well as its stability (FAO, 2017) ^[1]. The practices are significant in carbon sequestration in the atmosphere via biomass and in the soil via roots and soil organic matter (Lal, 2020) ^[4]. However, there is still a factor of constraint, which is water supply in the dryland areas and this will require the implementation of water-saving facilities such as rainwater collection and the micro-catchment systems that will be used to help in the growth of trees (UNCCD, 2020) ^[8]. Soil additions and organic inputs are another important method that could be adopted in order to enhance the process of carbon restoration in drylands (Paustian *et al.*, 2016) ^[5]. Application of organic soils such as compost, manure and biochar improves the soil organic content and improves the soil structure (Lal, 2004) ^[3]. In particular, it has been interested in biochar due to its stability and long-term permanence in the soils, thereby resulting in long-term carbon fixation (IPCC, 2019) ^[2]. These amendments also have the capability of making the soil more fertile and the work of the microorganisms required in the process of maintaining the nutrient cycle alive and to feed the plants (FAO, 2017) ^[1]. Advancement in remote sensing and geographic information system (GIS) has significantly contributed to the monitoring and assessment of the carbon restoration process in the dryland systems (IPCC, 2019) ^[2]. These technologies enable the collection of spatial and temporal data regarding vegetation cover, soil properties, and carbon stocks and, thus, get the restoration results refined to a greater extent (FAO, 2017) ^[1]. At a bigger level, the satellite information and modelling software are capable of determining the areas of degradation, the extent to which land use has changed, as well as the amount of carbon that can be sequestered (UNCCD, 2020). Such kind of data solutions can be essential to guide the policy and to provide maximum resources concerning the restoration efforts (Reed *et al.*, 2015) ^[6]. In addition to the technological plan, the utilisation of the traditional ecological knowledge and the application of the scientific approaches have also been considered a crucial component of an efficient carbon restoration plan (Reed *et al.*, 2015) ^[6]. The indigenous land management methods, which are adapted to the local environment, are water harvesting, mixed-cropping, and rotational grazing that are developed over centuries (FAO, 2017) ^[1]. With the adoption of these practices into the modern-day restoration systems, one can enhance their effectiveness and make them more acceptable to the residents (UNCCD, 2020) ^[8].

Applications

Carbon restoration has been discovered to have a high potential of improving the health of soils and increasing agricultural production in drylands, where the main constraints in sustainable agriculture are soil degradation and loss of soil nutrients (Lal, 2020) ^[4]. These activities increase the soil organic carbon (SOC) that results in the enhancement of the soil structure, porosity, and aggregation eventually increases the penetration of plant roots and uptake of nutrients (Paustian *et al.*, 2016) ^[5]. Studies have indicated that agroforestry activities can increase the

quantity of carbon stocks available in the soil by up to 30 percent compared to the conventional farming systems thereby improving the fertility of the soil and its long-term productivity (FAO, 2017) ^[1]. Planting trees and shrubs in farm scenery also provides some additional input of biomass that results in the formation of organic matter within soils (Reed *et al.*, 2015) ^[6]. Among the most important applications of carbon restoration to the drylands, it is possible to distinguish the contribution to the efficiency of the water usage and moisture retention in the soils (Reynolds *et al.*, 2007) ^[7]. A SOC enhances the capacity of holding water and this reduces the losses of water to evaporation and supply of water to the crops is sure during the dry seasons (Lal, 2004) ^[3]. It is particularly vital in dry regions, where such a possibility is infrequent and extremely uncertain and unpredictable, making the availability of water the restricting force of food production (UNCCD, 2020) ^[8]. Because of this, the high carbon soils are more easily able to support crop production during drought seasons and reduce crop failures thus the food security (FAO, 2017) ^[1]. Restoration of carbon besides enhancing soil fertility contributes a lot towards reducing the extent of climate change since carbon dioxide quantities in the atmosphere are reduced through sequestering (IPCC, 2019) ^[2]. The SOC levels may be used to offset a high percentage of the anthropogenic greenhouse gas emission by enhancing the carbon sinks in soils (Lal, 2020) ^[4]. Some of the restoration measures include conservation agriculture and reforestation, which increase the carbon input in the soil and reduce carbon loss, which eventually increases the overall carbon balance of the ecosystems (Paustian *et al.*, 2016) ^[5]. As well, carbon is stabilized in the soil aggregates so that it is not easily destroyed and released to the atmosphere thereby resulting in long term storage of carbon (Lal, 2004) ^[3]. Carbon restoration also plays a key role in enhancing resilience of ecosystems to climatic change and abnormal weather conditions (Reynolds *et al.*, 2007) ^[7]. The improved soil structure and the volume of the organic material will contribute to enhancing the capacity of the soil to absorb and retain water that will diminish consequences of droughts and floods (FAO, 2017) ^[1]. This kind of resilience becomes necessary in arid lands where climatic extremes are becoming increasingly frequent in the context of the change in climate, to support not only agricultural operations but also to protect livelihoods (IPCC, 2019) ^[2]. This is also true of the vegetation in the restored landscapes that functions to curb soil erosion since it makes the soil surface stable and protects against the forces of wind and water (UNCCD, 2020) ^[8]. The next important finding is that carbon restoration is useful in the conservation of biodiversity (UNCCD, 2020) ^[8]. Recreated ecosystems with longer vegetation cover provide space to a wide range of plant and animal species, which lead to the increase of ecosystem in terms of diversity and stability (Reed *et al.*, 2015) ^[6]. Improved biodiversity also leads to improved functioning of the ecosystems including nutrient cycling, pollination, and pest control which are required in the sustainable agricultural systems (FAO, 2017) ^[1]. In particular, agroforestry systems have been shown to contribute to the preservation of high biodiversity rates compared to monoculture systems of farming because they offer heterogeneous natural habitats, which support the

growth of different species (Paustian *et al.*, 2016) ^[5]. There are also significant socio-economic implications of carbon restoration activity, particularly to the rural communities in the dry land regions (UNCCD, 2020) ^[8]. The practices can enhance the livelihood of farmers and food security through raising soil fertility and agricultural productivity (FAO, 2017) ^[1]. In addition, sustainable land management practice will reduce the input rates since fewer chemical fertilizers and irrigation will have to be used (Lal, 2020) ^[4]. Most cases of restoration projects also offer employment within their regions such as planting of trees, land and surveying, thereby developing the rural regions (Reed *et al.*, 2015) ^[6]. Sustainable development strategies have also seen the use of carbon restoration in climate-smart agriculture go up (IPCC, 2019) ^[2]. In order to address the issue of climate change, climate-smart practices which introduce productivity, adaptation, and mitigation objectives have become popular in dryland regions (FAO, 2017) ^[1]. The practices include utilization of superior sources of crops, progressive water management, and harnessed soil fertility management, which aid in strengthening carbon sequestration and resilience of ecosystems (Paustian *et al.*, 2016) ^[5]. The better monitoring technologies also enhanced carbon restoration strategies since it was now possible to determine carbon stocks and changes in the ecosystem with more accuracy (IPCC, 2019) ^[2]. With the assistance of the tool of remote sensing and GIS, large-scale mapping of vegetation cover and soil becomes feasible to identify the areas damaged and evaluate the outcomes of the restoration process (UNCCD, 2020) ^[8]. The technologies have helped to make evidence-based decisions and optimize restoration efforts by prioritizing the areas in which carbon sequestration probable (FAO, 2017) ^[1].

Challenges and Limitations

Despite good potential, considerable number of biophysical, climatic and socio-economic barriers is associated with the use of carbon restoration in drylands that limits the viability and applicability of the technology (Reynolds *et al.*, 2007) ^[7]. One of the most significant constraints is the limited water that directly affects the vegetation growth and reduced contribution of organic matter into the soil (UNCCD, 2020) ^[8]. Not only is rainfall in dry land ecology very limited, but also highly unpredictable and it cannot support vegetation cover which could be employed in carbon capturing (IPCC, 2019) ^[2]. Poor soil quality, which is low nutrient content, weak structure and low content of organic matter are further limitations in the ability of the soils to retain and store carbon (Lal, 2004) ^[3]. This situation complicates the environment, and rehabilitation operations can in most instances be long- term investment and well-controlled to show observable outcomes (FAO, 2017) ^[1]. Climate variability and climate change also make it more complex in terms of carbon restoration activities in drylands (IPCC, 2019) ^[2]. The growing temperatures and changes in precipitations patterns will be some of the factors influencing plant growth, and it will lead to reduced biomass productions and an increase in organic matter breakdowns (Reynolds *et al.*, 2007) ^[7]. This effect of extreme weather events such as long droughts, heat waves, and other harsh rains can lead to disruptions in the restoration efforts and the resultant soil erosion (UNCCD,

2020) ^[8]. Such uncertainties make it hard to estimate the future success of the carbon restoration projects and will probably discourage investment in such projects (Lal, 2020) ^[4]. Moreover, the feed-back between the alterations in climate and degradation of land can be used as a part of the language of the restoration benefits (Paustian *et al.*, 2016) ^[5]. Socio-economic factors also play a supportive role in limiting the process and success of carbon restoration practices (UNCCD, 2020) ^[8]. One of the most significant challenges to get through is also the issue of insecurity of land tenure since farmers and land users may not want to invest in long-term restoration activities until they are sure that they own the land or at least have the right to access it (FAO, 2017) ^[1]. The systems of communal land ownership dominate most of the dry land areas thus hampering in making decisions and adoption of organized activities to restore the environment (Reynolds *et al.*, 2007) ^[7]. It is also limited by financial factors and lack of access to credits, so the ability of farmers to introduce practices such as agro forestry, conservation agriculture and soil amendments that in most instances could require start-up capital is curtailed (Lal, 2020) ^[4]. The second weakness is a lack of awareness and technical expertise of local communities of sustainable land management practices (FAO, 2017) ^[1]. Access to education, extension services and training programs is still not available, and this has seen many farmers continue with the traditional processes that could be contributing to soil degradation (UNCCD, 2020) ^[8]. This is also undermined by the absence of institutional support and capacity-building programs to disseminate and adopt the carbon restoration techniques (Reed *et al.*, 2015) ^[6]. Additionally, the cultural and social factors may also influence the introduction of new practices, which is why the restoration strategies should be adjusted to the local requirements (Paustian *et al.*, 2016) ^[5]. The use of technical and methodological barriers is also a hindrance to the achievement of carbon restoration in drylands (Paustian *et al.*, 2016) ^[5]. The sequestration of carbon is not easily monitored and confirmed due to the high spatial variability of the soil characteristics and the distribution of carbon in soil (IPCC, 2019) ^[2]. Organic carbon in soil can best be quantified through a large-scale sampling and laboratory analysis that can be both time-intensive and costly (FAO, 2017) ^[1]. In addition, lack of similar methodologies of quantifying and recording carbon stock introduces inconsistency in data and lowers comparability in researches (Lal, 2004) ^[3]. Such problems are also powerful impediments to the implementation of carbon credit and the promotion of restoration through the introduction of market-based instruments (UNCCD, 2020) ^[8]. The other major limitation is that it takes a long time to replenish carbon to the extent that measurable outcomes can be realized (Reynolds *et al.*, 2007) ^[7]. Being a long-term process, as compared to the short- term interventions of agriculture, carbon sequestration could take several years or even decades to produce any significant result (Lal, 2020) ^[4]. This is discouraging to the stakeholders notably the small holder farmers who require immediate profits so as to earn their livelihoods (FAO, 2017) ^[1]. Also, the benefits of

carbon restoration such as healthier and stronger soil are not always immediately apparent which is why it is not always simple to promote a mass usage (Paustian *et al.*, 2016) ^[5]. Carbon is not replenished by drylands since institutions and policies do not go hand in hand. According to UNCCD (2020) ^[8], plans that align land management to climate action and rural growth are lacking in most parts. This is supported by IPCC (2019) ^[2] - policies are either distributed or not. Years of investment is not enough to turn things around. Poor governance and ruptured regulations allow degradation to persist (Reed *et al.* 2015) ^[6]. Government agencies, local groups, and NGOs do not cooperate with each other (FAO, 2017) ^[1]. Lack of a common vision and trust leads to a breakdown in programs. Drylands reduce the carbon gains due to loss of biodiversity, invasion by other species as well as soil salinization (Reynolds *et al.* 2007) ^[7]. Poor biodiversity conditions the capacity of the ecosystem to perform and recuperate. Native species are replaced by invasive plants and prevent the storage of carbon at the ground level. Poor irrigation results in salinized soils (Lal, 2004) ^[3]. Bad water use kills plants. Plants, no roots, no organic, no material. Carbon cannot be stored in the long term without growing plants.

Future Perspectives

The concept of the carbon restoration of degraded and drylands in the future must be more concerned with developing location-specific approaches that suit the local ecological, climatic, and socio-economic realities of those areas (Lal, 2020) ^[4]. Drylands are highly heterogeneous landscapes with variation in rain-fall patterns, soil type and vegetation cover making a considerable contribution to carbon-processing/restoration-potential (Reynolds *et al.*, 2007) ^[7]. Thus, the one-solution strategy will not bring the best results, and more specific interventions according to the thorough evaluation of the environment are needed to enhance the efficiency of the restoration interventions (Paustian *et al.*, 2016) ^[5]. In this regard, the field experiments and area-specific studies are required to be taken over the long term to comprehend the relationship between management practices and carbon sequestration in various dryland ecosystems (IPCC, 2019) ^[2]. The combination of conventional ecological knowledge and modern scientific methods will probably be very important to create future plans of carbon restoration (Reed *et al.*, 2015) ^[6]. Water harvesting, mixed cropping, and rotational grazing are adaptive land management techniques practiced by the indigenous communities of dryland regions over generations and are strongly adapted to the local conditions (FAO, 2017) ^[1]. These practices that have proven over time when combined with scientific innovations have the potential to improve the results of restoration by providing ecological viability and social acceptance (UNCCD, 2020) ^[8]. Moreover, the implementation and success of restoration projects and programs can be enhanced through participatory strategies that include the local communities in decision making (Reynolds *et al.*, 2007) ^[7]. In the future, technological progress is predicted to contribute greatly to monitoring, assessing, and streamlining carbon restoration initiatives (IPCC, 2019) ^[2]. Remote technologies, such as satellite imaging and drone-mounted surveillance allow obtaining high-resolution data on vegetation cover, land use

alterations, and soil characteristics, which are more precise in estimating carbon stocks and the processes within the ecosystem (FAO, 2017) ^[1]. Moreover, predictive modelling of the potential of carbon sequestration and prioritization of the restoration areas can be performed with the help of the integration of Geographic Information Systems (GIS) and machine learning algorithms (Paustian *et al.*, 2016) ^[5]. The real-time monitoring and adaptive management can also be supported by these tools and beneficial changes to the restoration strategies on the basis of the observed results can be provided in time (UNCCD, 2020) ^[8]. New technologies like digital soil mapping and carbon accounting systems are also likely to enhance the measurement and validation of the carbon stocks in soils (Lal, 2020) ^[4]. Carbon sequestration needs to be properly measured and recorded to be integrated into carbon restoration in global climate mitigation strategies and carbon markets (IPCC, 2019) ^[2]. It will be essential to have standardized methods and effective monitoring tools to bring transparency and credibility to the work of carbon accounting to attract investment and policy incentives to support restoration efforts (FAO, 2017) ^[1]. The financial incentives and support in policy-making will be a central factor in implementing carbon restoration in dryland areas on a large scale (UNCCD, 2020) ^[8]. Governments and international bodies are beginning to appreciate the value of sustainable land management to the realization of climate and development targets, and this has resulted in the enactment of policies to encourage restoration practices (IPCC, 2019) ^[2]. Economic incentives like carbon credits, subsidies, and ecosystem services payment may be used to motivate farmers and land managers to practice methods that enhance carbon (Lal, 2020) ^[4]. Moreover, to make carbon restoration a permanent obligation and resource distribution, it is possible to make it a part of national climate action plans and sustainable development frameworks (FAO, 2017) ^[1]. Carbon restoration efforts will also require capacity building and spreading knowledge to achieve success in the future (Reed *et al.*, 2015) ^[6]. The technical skills and awareness of farmers and land users can be improved through training programs, extension services or education campaigns to be able to implement the sustainable practices efficiently (UNCCD, 2020) ^[8]. Institutionalization of frameworks and encouraging partnerships between research institutions and government bodies as well as non-governmental organizations may also help in making the best practices and knowledge widespread (Paustian *et al.*, 2016) ^[5]. The implementation of sustainable practices between governments, researchers, and local populations is needed to attain long-term carbon restoration goals (FAO, 2017) ^[1]. The resources, expertise, and information can be shared amongst multi-stakeholder partnerships and which result in more integrated and effective strategies of restoring (Reynolds *et al.*, 2007) ^[7]. The transboundary issues, i.e. desertification and climate change, are especially significant to be managed through international cooperation since they demand collective efforts across regions and nations (UNCCD, 2020) ^[8]. Moreover, there is a need to investigate the possibilities of such innovative solutions as biochar application, microbial inoculation, and climate-resistant crop varieties to promote carbon sequestration in drylands

(Lal, 2020) ^[4]. These new technologies have demonstrated potential to enhance soil fertility, enhance growth of biomass, as well as stabilize organic carbon in soil (Paustian *et al.*, 2016) ^[5]. Nonetheless, their dryland performance needs to be researched further in order to make them scalable and sustainable (IPCC, 2019) ^[2].

Conclusion

The phenomenon of carbon restoration of degraded and dryland systems is also a valuable approach to climate change and, at the same time, the more robust, sustainable ecosystems (Lal, 2020) ^[4]. The dry land ecosystems being delicate and highly vulnerable to degradation need special interventions to reestablish the ecological balance and productivity of the ecosystem (Reynolds *et al.*, 2007) ^[7]. Restoration practices help achieve sustainable agricultural systems by increasing soil health, nutrient cycling, and water retention through improvement of soil organic carbon (SOC) in resource-constrained soils, leading to better resource management (Paustian *et al.*, 2016) ^[5]. Not only do these enhance productivity of crops, but also make agricultural systems more resilient to climatic stresses like drought and fluctuations in temperature (FAO, 2017) ^[1]. Carbon restoration is not just important to improve the soil, it is also critical in reversing climate change through carbon sequestration (IPCC, 2019) ^[2]. Biofuel production reduces the amount of carbon dioxide in the atmosphere by increasing the stocks of SOC, which is one of the strategies taken by the global community to contain global warming (Lal, 2020) ^[4]. Moreover, recreated ecosystems have several co- benefits such as the protection of biodiversity, better ecosystem services, and landscape stability (UNCCD, 2020) ^[8]. Practices that include agroforestry, conservation agriculture, and regenerative grazing have proven to provide the capability to develop multifunctional landscapes to balance productivity and environmental sustainability (Reed *et al.*, 2015) ^[6]. Even with benefits, pushing carbon restoration in drylands hits roadblocks from environmental, socio- economic, and institutional problems (Reynolds *et al.*, 2007) ^[7]. Water shortages, poor soil, and climate shifts keep undercutting efforts and making outcomes worse (IPCC, 2019) ^[2]. Land rights remain shaky. Farmers often lack money or the know-how to manage land properly (FAO, 2017) ^[1]. It seems hard to ignore how policy and local knowledge must come together to work. A single approach won't cut it. Solutions need science, real-world guidance, and community input (UNCCD, 2020) ^[8]. Governments, scholars and local communities should collaborate and co-design context-based restoration measures if they want to address the problem of these limitations (Paustian *et al.*, 2016) ^[5]. The policy frameworks that include sustainable land management and financial support through carbon sequestration can serve as a real motivator in getting restoration practices rolled out at a much larger scale (Lal, 2020) ^[4]. Besides, technologies such as remote sensing and data-driven modelling along with carbon monitoring and restoration optimization offer new avenues (IPCC, 2019) ^[2]. When combined with the traditional ecological knowledge, such innovations can help restore drier land areas in a more effective and resilient way (Reed *et al.*, 2015) ^[6]. A further research and innovation are needed to create scalable and efficient carbon restoration

approaches that may be implemented in various drylands (FAO, 2017) ^[1]. To optimize the relations between soil, vegetation, and climate, along with socio-economic aspects that determine the results of the restoration process, long-term studies are required (UNCCD, 2020) ^[8]. This type of knowledge will be essential in the development of adaptive management strategies that will be able to adapt with the evolving environmental states and the eventual success of the restoration projects (IPCC, 2019) ^[2]. Lastly, carbon restoration offers a different and medium-term option for achieving environmental sustainability, combating climate change, and socio-economic development in drylands (Paustian *et al.*, 2016) ^[5]. Such measures may be a boon to the millions of people dependent on dryland resources, besides meeting global sustainability targets, also revitalizing soil and ecosystem resilience (Lal, 2020) ^[4]. Carbon restoration plans have to be deeply rooted in scientific knowledge, policymaking, and grass-roots community action in order to be truly effective leading to the productive landscapes of the future generations as well as find a way to degraded landscapes (UNCCD, 2020) ^[8].

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