

# Rangelands as Carbon Sinks to Mitigate Climate Change: A Review

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## Abstract

Rangelands cover large areas in the United States and across the world and are natural carbon sinks which if properly managed and maintained can sequester substantial amounts of atmospheric carbon dioxide in the form of soil organic carbon and mitigate climate change. Varied climatic conditions impact carbon sequestration at the arid and semi-arid ecological sites on rangelands. Best management practices, site-specific policies and technological options are important approaches to manage these ecosystems to mitigate the impact of current climate variations. There are a number of co-benefits associated with management of rangelands for carbon storage, these include; improve soil quality and resilience, agronomic productivity, advancing global food security and restoring ecosystem diversity. Also, the non-equilibrium model is proposed for use on these xeric sites of rangelands since it better reflects the ecological dynamics that impact carbon sequestration and as such policies should be embodied this understanding. More studies are needed on the ecological dynamics, and factors that affect soil carbon sequestration process and mechanisms on arid and semi-arid environments as well as the soil organic carbon residence time so as to better our understanding of these regions. The voluntary carbon market was a good approach for stimulating carbon sequestration on rangelands, however the causes of failure should be revisited, addressed and necessary amendment to policies made that will be the driving force towards environment restoration and conservation. Some of the obvious challenges and opportunities with regards to efficient use of rangelands as carbon sinks to mitigate as well as adapt to climate change are discussed in this paper.

**Keywords:** Carbon sequestration; Agro-ecosystem; Interseeding; Carbon sinks; Semi-arid environment; Rangelands, Climate Change

## Introduction

### Utilization of rangelands as carbon sinks to mitigate climate change

Current climatic conditions continue to show temperature extremes which coincide with increasing atmospheric carbon dioxide while the call for reduction in Greenhouse Gases (GHGs) emission escalates, at least in the literature. Carbon dioxide contributes heavily to global warming and a large quantity of anthropogenic activities produce carbon dioxide as the major by-product [1]. While climate change is projected to exacerbate more focus should be geared toward improving the naturally available carbon sinks and efficient technology put in place for removal and fluxing of atmospheric carbon dioxide in these sinks. The IPCC [1] is of the view that if GHGs emissions are not addressed now by 2100, the average global temperature will reach 3-7%. Emitted carbon dioxide has an atmospheric residence time of up to 100 years [2] so while we continue to peak the call for reduce GHGs emissions there is also the need to improve sinks and intensify its removal, sequestration and storage from the atmosphere if we are to effectively mitigate climate change.

Evidence of climate change is seen in the increased average sea level, violent weathers and spread of diseases [2]. Soil structure breakdown is obvious and this is as a result of land misuse, soil mismanagement and climate variation, this impacted greatly on the terrestrial face, ecosystem services and biodiversity of the agroecosystems [3,4]. This therefore, means best land management practices, site-specific technologies, and policies that depict rangelands dynamics are essential to improve Soil Organic Carbon (SOC) stock, soil quality and longevity. Adoption of Recommended Management Practices (RMPs), best management practices, land restoration, improved ecosystem biodiversity; better understanding of climate-plant-soil-microbial interactions and introduction of technological methods can greatly impact the rate of carbon sequestration, SOC pools and soil quality on rangelands. This review focuses on features of U.S rangelands, protocols and

management practices available for carbon sequestration, soil quality on rangelands and their potential to extract atmospheric CO<sub>2</sub> and store it in a stable form thusly mitigating climate change.

### Rangelands soil organic carbon stock capacity

Rangelands include savannas, prairies, grasslands and shrub lands that are not cultivated and account for more than 750 million acres in the United States [5]. The world's agroecosystems (rangelands, croplands, and grazing lands), soil biota and non-soil biosphere are not effectively managed and they are very important carbon dioxide reservoirs that could off-set fossil fuel emission and mitigate climate change through carbon sequestration. The agroecosystems have the capacity to sequester 1.2- 3.1 billion tons of C/yr, and achieve cumulative potential of 30-60 Pg (Pg= petagram =10<sup>15</sup> g) over a 50 year period that could off-set up to a third of the yearly increase in atmospheric carbon dioxide that is estimated at 3.3 pg C/year [6,7]. This means minimal changes with respect to management in soil carbon sequestration across rangeland ecosystems could have a great impact on offsetting GHG emissions.

Rangelands can be large carbon sinks since they are one of the most widely distributed landscapes in the world. Approximately 30% of the ice-free global land surface is in rangelands that have up to 30% terrestrial carbon stocks [8,9]. Rangelands have the potential to remove 198 million tons of CO<sub>2</sub> from the atmosphere per year for 30 years

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and when saturation is achieved they could off-set 3.3% CO<sub>2</sub> emission in the U.S from fossil fuel [10,11]. Since reduction in anthropogenic greenhouse gases emission may not accomplish enough on its own, the need to sequester carbon already emitted to the atmosphere into stable forms is worth exploring and rangelands provide the most viable, ready to implement, environmentally friendly and costs effective way when compared to geologic and ocean sequestration [11].

### Soil organic carbon pool

Batjes [12] reported that the SOC pool is estimated at 2500 billion tons to 2-m depth and has been depleted considerably as a result of several soil degradation processes and due to conversion from natural to agricultural ecosystems. The SOC pool of agroecosystems is drained by some 25-75% depending on soil structure and holistic management practices being employed [6], hence management can achieve a lot on rangelands. Deforestation, biomass burning and soil erosion contribute heavily to reduction of SOC pool, creating a large carbon deficit [13]. The soil carbon debt is further exacerbated by practices including cultivation of peat lands, combustion of animal dung as domestic fuel and removal of crop residues that aggravate the loss of SOC [14].

The process of carbon sequestration on rangeland soils can increase the SOC concentration, enhance the SOC pool and off- set anthropogenic GHGs emissions. This does not only mitigate global temperature rise (each ton of carbon incorporated in the soils removes 3.67 tons atmospheric CO<sub>2</sub>) but also improve agronomic productivity, advance global food security and enhance soil resilience [6]. Climate change, particularly drought, may impact greatly on rangelands SOC pools, changing them from sinks to emission sources due to the xeric nature of the soils which directly affect the photosynthetic rates than total respiration rates [15]. Improved understanding of the processes and mechanisms that affect SOC dynamics on arid and mesic environments, coupled with land management and technology must be the focus for rangeland soils to accumulate and conserve carbon. The attention must be shift to breeding and growing drought tolerant plants with deep root system, growing leguminous crops, and more insight into microbial function and processes that impact carbon sequestration [16], so as to enhance the SOC pool, improve aggregation of soil particles, prevent erosion and increase ecosystem diversity in a changing climate. Soil C sequestration can be achieved by roots and hyphae as they have the ability to entangle soil particles, emplacing and releasing organic compounds that promote aggregation of particles [17].

The carbon sequestration rates are usually determined by the carbon inputs and outputs net equilibrium, which are affected by management, production of Soil Organic Matter (SOM) and decomposition of organic matter by the soil organisms and climatic variation. The net rate of soil carbon sequestration and storage may increase if the microbial metabolic process and CO<sub>2</sub> production is lessen. However, biochemical recalcitrance (remnants of undecayed compounds that becomes less decomposable), chemical stabilization and physical protection of SOM by soil aggregates are three ways to counter the increase CO<sub>2</sub> production [18].

Metric ton carbon dioxide equivalent (MTCO<sub>2</sub>e) is the standard measurement for the amount of CO<sub>2</sub> sequestered in the soil as SOC. Carbon sequestration rates are calculated using CO<sub>2</sub> flux data also the dry combustion and CO<sub>2</sub> emission method or the more classical Walkley-Black chromic acid wet oxidation method are applicable [19]. However, different quantification methods are harnessed an d used, each of the Measurement, Monitoring and Verification (MMV)

methods may be applicable based on cost, suitability and ease of use for a national trading platform, hence, a rangeland soil carbon protocol methodology is once utilized that harness a combination of methods which may be placed along a conceptual spectrum, with high confidence levels (and expense) at one end and ease of use (and data coarseness) at the other end and a successful methodology lies between the two poles [20].

Soil carbon constitutes the SOC and Soil Inorganic Carbon (SIC). SOC is a dynamic group of compounds formed from carbon originally harvested from the atmosphere by plants via photosynthesis. SOC plays a pivotal role in nutrient cycles as it is a potent source of energy and growth in the plants. SIC is a product of mineral weathering usually in the form of carbonate, and not as responsive to management as SOC. The SOM has approximately 50% SOC, while soil microbial biomass carbon is about 1-3% of total soil carbon [21]. Rangeland soil accounts for approximately 90% of the carbon in comparison to the aboveground biomass [22]. Clay and iron greatly impact the soil organic carbon and reduce the bulky density of soils. SOM influences fertility, productivity and stability of the soil. Also, the water holding capacity, pH and soil temperature are buffered by SOM and SOC [23]. SOM increases the air spaces of soil pores and surface area, impacting positively on water and nutrients retention which is especially very important on US rangelands which experience less than 600 mm precipitation yearly [20]. Increasing the rate of processes that govern C sequestration will increase SOC pool resulting in a more fertile soil that promotes vegetation growth especially on arid and semi-arid ecological sites where the ecosystem dynamics is not well studied.

### Rangeland ecosystem dynamics

Booker et al. [24] reported that rangeland management will achieve very little for carbon sequestration because the dynamics of rangelands are not well understood; and proposed and current carbon sequestration policies and grazing management recommendations in the United States are designed based on the equilibrium ecological model instead of the non-equilibrium model which better depicts rangeland ecosystem dynamics. Climate change greatly impact the soil structure and vegetation on agroecosystems, particularly at the arid and semi-arid regions where soil water is limited. Site-specific RMPs, Conservation Reserve Programs (CRPs), grazing management practices should contain protocols that address the ecosystem services and depict the dynamics of the ecosystem at different sites. More emphasis is put into management of croplands and improved pastures even with the unpredictable climate change, and some of these practices can be adapted to rangelands. The rangeland ecosystem dynamics must be addressed, improved and policy oriented if the soil and the nonsoil biosphere are to effectively act as carbon sinks [24]. Selective plant breeding and cultivation can be done in areas of rangelands that encounter severe soil stress, Integrated Nutrient Management (INM), soil amendment strategies (biochar), afforestation, restoration of degraded lands and adoption of site-specific RMPs are necessary to improve the SOC content and stabilize the soil structure at the xeric end of rangelands climate gradients.

Management in of itself cannot reliably increase carbon stock on arid and semi-arid rangelands. With improved knowledge of the ecological dynamics, ecological sites and distribution management can be more responsive, and to date, a site-specific predictive model is still not available [25]. Special consideration to ecological site and link to 'best fit' ecological model is deemed important so as to assess the carbon sequestration potential on rangelands [26]. Rangeland soils can effectively sequester carbon, if policies are consistent with the

ecological science of these landscapes, Booker et al. [24] elucidated four policy principles that should be implemented so as to remove monetary focus and replace rangeland conservation efforts: policy should (1) not require short-term explicit carbon counting (2) not assume that changes in management can create additional carbon sequestration (3) not use arid rangeland sequestration that is not consistent and verified to off-set emissions; and (4) should focus on conserving rangelands or reverting degraded agricultural lands to rangelands. Application of these principles to proposed rangeland carbon sequestration policies would shift the attention from focusing on annual fluxes and attain long-term protection, soil carbon conservation, and host of environmental and social benefits [24].

### Carbon sequestration on rangelands: protocol and policy

There is sufficient evidence of climate change and the effects are widespread. The 14 warmest years have been observed and all occurred since 1980, while the two hottest years on record were 1998 and 2005 [2]. As science continues to unleash a wealth of knowledge on climate change and increasing levels of GHGs, governments are yielding slowly to management practices and environmental restoration policies that will seek to develop carbon sinks and mitigate emissions of these pollutants.

In 1992, the first treaty was signed in Rio de Janeiro, Brazil, calling for the reduction of CO<sub>2</sub> and other GHGs by industrialized nations to 1990 levels by 2000 [2]. The proposal was not binding and as such was not met. The UN Framework Convention on Climate Change proposed the Kyoto protocol which was adopted in 1997 and enforced in 2005 [7]. The treaty required the industrialized nations to reduce their fossil fuel emissions by 5% below the 1990 levels by 2012 but developing countries were exception to the treaty. By 2011, the protocol was signed and ratified by 191 states except the U.S. The U. S was required to reduce its GHGs emissions to 93% of the 1990 levels which had increased to about 18% since. Then in 1998, the U. S. along with 106 nations agreed to begin implementation of the Kyoto protocol. The protocol was revised in Bonn in July 2001 comprising of two new clauses relevant to SOC sequestration:

- 1) Countries are allowed to subtract certain increases from their industrial C emissions if C was sequestered in 'sinks' such as forest and soils; and
- 2) Trading of emission allowances that can reduce abatement costs was also allowed. Providing that standard procedures were verified to assess the rate of SOC sequestration and cumulative magnitude. The UNFCCC/Kyoto Protocol recognizes soil carbon sinks.

Following the revision of the Kyoto Protocol, the 'clean skies and global change' initiatives along with two voluntary alternatives to the Protocol were announced by President Bush:

- 1) "We look for ways to increase the amount of carbon stored by the American farms and forests through strong conservation title in the Farm Bill" (President Bush, 14 February 2002)
- 2) There subsists a room for "sequestration of GHGs in agricultural and forestry sinks" (Economic report to the U.S. Congress, 2002).

Rangeland management can achieve a lot for carbon sequestration making them attractive carbon sinks, and as such identifying and implementing policy instruments should not be disregarded in an attempt to do so. Restoration of degraded soil and ecosystems as well

as increasing the SOC pool must not be ignored from a global policy perspective; it's just being environmentally friendly. Not only that these sinks will filter the excess CO<sub>2</sub> in the atmosphere but also increase soil structure, agricultural productivity and resilience while mitigating climate change. The Clean Development Mechanism (CDM, Article 12), emission trading (Article 17) or joint implementation activities (Article 6) of the Kyoto Protocol may also provide entrustment in SOC sequestration.

In 2003, the Chicago Climate Exchange (CCX) trading program, which was the world's largest rangeland soil carbon offset program, was introduced [2,25]. The aim of the program was to give air pollution credits to firms that exceed emission-reduction goals. A minimum of 5 year contractual commitment was required by rangeland project managers, and nondegraded and previously degraded rangelands were also eligible for carbon sequestration projects if they adapt improved grazing management practices: light to moderated stocking rates, appropriate distribution, proper season of use, and rapid drought response systems on rangelands [26]. An independent CCX-authorized verifier also conducts in-field inspections at least once per year to ensure policy practices are met.

Modification of existing land conservation programs to include SOC management is currently attracting attention among researchers and policy makers [27]. Many of these amendments have been discussed in the literature, inclusive of studies on lands enrolled in the CRP and facts sheets issued by the Conservation Innovation Grant program and the Conservation of Private Grazing Land initiative as reviewed by Schuman et al. [8]. With better understanding of why rangeland owners participated in existing conservation programs as well as implementation of conservation practices may provide insight for identifying features that will attract the interest in carbon sequestration [27].

Some policies and most proposals for the cap-and-trade and payment for environmental services offer incentives for increasing the average carbon flux annually from the atmosphere to soils through management changes. However, it is difficult to sequester carbon at the xeric end of rangelands and as such insignificant and in some cases negative net carbon flux is likely even if we assume that management practices can increase terrestrial carbon sequestration [27]. The four policy principles reported on for rangeland ecosystem dynamics for carbon sequestration on arid U.S. rangelands that would make them modern rangeland ecology were proposed in acknowledgement of the deficient at these sites.

### Rangeland carbon credit and carbon offset

Carbon fluxes on rangelands are influenced by several factors such as precipitation, temperature, vegetation and soil properties that can counter frequently used and well-understood management practices, as such, focus on offset projects that target the management of lands to soil carbon storage is necessary. Development of cost effective carbon sequestration projects that are dependent upon, accounting for, and managing the uncertainty inherent in rangeland ecosystems and projects is also necessary [25].

A Sustainably Managed Rangeland Soil Carbon Sequestration Offset Project protocol was initiated by the CCX in 2009 which required a long term (minimum 5 years), legally binding commitment that explained management practices which increases soil carbon stocks on Rangelands in specific geographic areas to management. The project aimed at increasing soil carbon stocks through practices that identify

and accommodate periods of grazing, ensure sustainable forage-animal balance and provides for a contingency plan for management during drought. Having recognized that actual carbon sequestration on rangelands varies with management practices, ecological sites, and climate conditions, as part of a conservative approximation of the mean soil carbon uptake, CCX established the Offset issuance rates which are discounted from the mean of the range of the soil carbon sequestration values.

20% of the offsets earned by each CCX rangeland soil project was placed in a Soil Carbon Reserve Pool account as a precaution against reversal in carbon sequestration due to failure to follow contractual management practices and/or drought occurrence but shall remain the property of the project owner(s) upon satisfaction of the five year agreement [28]. The CCX reserved the right to prohibit project owners from future participation if they failed to conform to the practices specified in the contractual agreement. An agent called the Offset Aggregator is responsible for combining and forming a larger trading unit for project owners involving less than 10,000 metric tons of CO<sub>2</sub> per year.

De Steiguer et al. [25] reported on a study in Wyoming that examined the costs of creating offset credits on a 40, 000-acre cow/calf operation through a variety of practices such as sagebrush thinning, alfalfa interseeding, movement of cattle from sensitive grazing areas during the summer and fencing. The findings showed that, over a 20-year period, carbon credits could attract a cost between \$8 and \$17 per MTCO<sub>2</sub>e which would make rangelands compete favorably with croplands and forest lands for sale of carbon credits. However, CCX offset credit prices as of 2008, were lowest of all times, ranging from below \$1 to above \$5 per TCO<sub>2</sub>e.

De Steiguer et al. [25] also highlighted another study of carbon sequestration on semi-arid state-owned rangelands in Arizona in which a simulation of range management conditions was done for 12 different soil profiles. The results indicated that some semi-arid rangeland soils could provide economic opportunities seeing that the soils could be candidates for carbon offsets management.

### Private land management incentivization

Approximately 254 million acres (100 million ha) of private grazing lands are in the U.S. having the capability to store an additional 60 million tons of C (220 MTCO<sub>2</sub>e) per annum [25]. While conventional conservation programs aimed at preserving the soil structure and maintaining the ecosystem, carbon sequestration practices may be integrated or potentially amend these programs to improve the SOC content and maximize the soil carbon storage potential. Rangeland management policy for C sequestration practices should educate and incentivize private rangeland owners of the environmental benefits that are associated with increasing the SOC pool.

A current study of private rangeland owners from Utah showed little interest (37%) for potential participation in a carbon sequestration program if it should be initiated, taking into consideration its climate and financial gains associated [27]. The lacking in interest for participation in the program was explained to be as result of little knowledge of soils ability to act as a carbon reserves through enhanced carbon sequestration by improving the rangeland biospheres. Cook and Ma [27] added that special emphasis is needed to develop innovative strategies that will actively communicate the C sequestration process with rangeland owners as well as ways of making land management more attractive.

To further incentivize agricultural and private landowners to management of their lands in an effort to mitigate climate change through C sequestration, the Chicago Climate Exchange (CCX) carbon market was developed in 2008. This was program that allowed ranchers to participate in a voluntary carbon market through generating, trading and selling carbon credits. Thus, in 2009 the CCX Sustainably Managed Rangeland Soil Sequestration Offset Protocol too effect and the Trigg family enrolled some 50,000 acres of rugged rangelands and earned \$90,000 after selling the carbon credits generated to an energy company in Texas [29]. The Trigg family was also the first rancher in the state to register and sell credits from state-owned land. Since some ranchers were not familiar with the details of the carbon sequestration process, monetary incentive was unattractive and they were more in support of the co-benefits associated with management [30,31]. Albeit, the program is no longer active [29], we have seen where its economic benefits can be of importance to rangeland owners who are considering transitioning rangelands into carbon dioxide sinks and to part take in carbon markets if they should be re-initiated in the future.

Incentivization through Payment for Ecosystems Services (PESs) is another market-based avenue that could indemnify land managers for environmental management and protection through soil conservation and ecosystem restoration while enhancing the carbon stock [32]. Sommerville et al. [33] added that a PES implementation framework is needed to form that vital element in creating positive incentives that will influence decision making behavior. Also, an ecological function subject to trade, establishment of standard units of exchange, and a supply-demand and intermediation flows between those who sell and buy ecosystem services are some characteristic features that must be addressed for economically rewarding resource management through PESs [34].

In addition, US government policies are increasingly more conservation-direct as it relates to private rangeland management, this is largely supported by programs in the 2002 Farm Bill [16], which include the (1) "Conservation of Private Grazing Land Program, (2) Conservation Security Program, (3) Environmental Quality Incentives Program, (4) Grassland Reserve Program, (5) Wildlife Habitat Incentives Program and (6) Wetlands Reserve Program, "however, these programs were more so forms of pecuniary incentives but can be modified to increase C sequestration interest with best management practices.

## Land Management Practices- Current and Proposed

### Grazing management practices

The literature explains grazing to be one of the management practices that aid in the physical break down, increase rate of residual plant material decomposition and soil incorporation, hence, restoration of badly degraded rangeland soils [16]. The group summarizes the effects of different management practices on SOC sequestration rates on rangelands across ecosystems. They focused mainly on grazing, nitrogen fertilization, legume interseeding and restoration practices in different locations and how they impact SOC sequestration rates with time. Several other studies have shown that grazing intensity and frequency may impact greatly on carbon storage in some areas on rangelands, albeit the effects are usually difficult to foretell and often times inconsistent due to opposition from abiotic factors.

Heavy and continuous cattle grazing have deteriorated grasslands over many years resulting in severe soil disturbance [16,24]. In some cases, short term light or heavy grazing induced changes in plant

species composition contributes to increase in SOC content [16]. The group highlighted an example during a grazing season where moderate and heavy stocking rates were employed in a shortgrass steppe and a northern mixed-grass prairie. The results showed a modified plant community composition where the proportion of cool-season (C3) perennial grasses were reduced while an increased in the predominant warm season (C4) perennial grass, blue grama population was observed and a reduction in the production potential of rangelands by up to 33%, but increases the SOC because there was greater transfer of carbon to belowground plant parts in blue grama.

In an attempt to discuss the effects of management on SOC sequestration, Derner et al. [16] highlighted a study where estimated increases in soil C sequestration rates of  $0.12 \text{ Mg C ha}^{-1}\text{yr}^{-1}$  (108.78 lbs  $\text{ac}^{-1} \text{ yr}^{-1}$ ) and  $0.07 \text{ Mg C ha}^{-1}\text{yr}^{-1}$  (63.46 lbs  $\text{ac}^{-1} \text{ yr}^{-1}$ ) in the soil surface 30 cm were observed when subjected to grazing at moderate and heavy stocking rates respectively in a shortgrass steppe compared to adjacent non-grazed enclosures. Increase in SOC was also observed during light or heavy stocking rates in northern mixed-prairie ( $0.30 \text{ Mg C ha}^{-1}\text{yr}^{-1}$  or  $271.96 \text{ lbs ac}^{-1} \text{ yr}^{-1}$ ) while rotationally-deferred grazing, short-duration rotational grazing and continuous season-long grazing at heavy stocking rates, did not affect carbon sequestration in a northern mixed-grass prairie. This variation in SOC sequestration hints to the complexity of interaction of management and environmental conditions. Schuman et al. [35] reported that severe drought and heavy grazing can culminate significant deficits in SOC that was previously stored, and also shift the microbial community resulting in further losses in soil C. This means more emphasis must be concentrated on addressing the interaction of management and the environment.

Booker et al. [24] explain that much of the focus to increase carbon sequestration on rangelands is geared towards grazing management yet the effects on carbon cycling are usually unpredictable. They reason that abiotic factors often times dominate the natural processes such as grazing on arid rangelands because the ecological sites are usually not well understood and underrepresented in grazing studies, and this accounts for the variability observed in SOC sequestration rates. As a result, manipulating grazing systems on the abiotically-controlled non-equilibrium arid systems of the rangelands in the US will not give rise to significant carbon sequestration or stocking [36], but more so impacting on vegetation state transitions.

Booker et al. [24] supported the idea that grazing on a particular ecological site may influence increasing growth of woody plants such as shrubs, which may positively impact the carbon dynamics. This is because shrub growth can sequester more carbon in woody material that lingers for longer time in the soil compared to herbaceous plants [37]; however, this is dependent upon the ecological site and the grazing system employed [24]. The absence of water in rangeland soils at the xeric end of the climatic gradients with heavy grazing can give rise to the growth of woody shrubs while the presence of water coupled with light grazing can contribute to increase woody shrubs density [24]. In addition, they found that organic carbon is suggested to be better retained in drier regions compared to wetter regions because the latter regions are prone to oxidative carbon losses owing to the increase woody vegetation density. Also, with increased growth of woody shrubs, grass population may reduce, as a result of root competition and shading, giving rise to soil exposure and deterioration which could mean loss in soil carbon stock. Attempting to strike an ecological diversity balance in species composition in these regions by manipulating the woody vegetation density and grass growth through grazing management practices, where possible, together with a better understanding of

vegetation state transition, can have tremendous effect on soil carbon stock, thus, making the soil more resilient to climate change.

After the Trigg family enrolled some acres of badly degraded rangelands in the CCX program, they decided to restore the soil via a transition to holistic management practices (HMPs) [29], which were in alignment with the CCX Rangeland Offset Protocol [28], since prior grazing management practices yielded little carbon. They did HM courses and got technical and financial support through the USDA, Natural resources Conservation Services (NRCS) and Environmental Quality Incentives Program (EQIP). Their biggest challenge was modifying the location and grazing pattern of the cattle especially if they were subjected to extensive grazing for long periods. With the support of a grazing management consultant, they organized the pasture into management areas based on ease of movement and terrain, reduced the size of the paddocks to attain the infrastructure for rotational stocking and reduced stocking periods. The result of implementation of rotational stocking, planning and documenting activities was improved vegetation and more resilient grasses, and better distribution of perennial shrubs thus, contributing to better soil water usage and reduced erosion.

### Nitrogen fertilization

In a review, Derner et al. [16] use previous field study results to show that sufficient nitrogen input can increase production and water use efficiency, since rangelands are usually deficient in nitrogen. Management practices using Tall grass prairie and CRP on Kansas, Wyoming and Saskatchewan rangelands have yielded increase soil C sequestration rates of  $1.6 \text{ Mg C ha}^{-1}\text{yr}^{-1}$ ,  $0.41$  to  $1.16 \text{ Mg C ha}^{-1}\text{yr}^{-1}$ , and  $5.4$  to  $9.3 \text{ Mg C ha}^{-1}\text{yr}^{-1}$  respectively. In another study in Oklahoma, SOC changes on “WW-Spar” Old World bluestem pastures were even greater after five years of annual intermediate N fertilizer application. Although nitrogen input supports increase SOC sequestration, the benefit is offset by  $\text{CO}_2$  and  $\text{N}_2\text{O}$  emissions and  $\text{CH}_4$  uptake in soils during the application process, this is more so evident for croplands. Fertilization can be costly and as such this is not a permanent method for improving the soil quality on rangelands but an intermediate step to achieve good soil structure that will be more resilient to climate changes in years to come.

### Legumes interseeding

As a result of nitrogen application drawback, the thought of nitrogen fixing legumes on rangelands has been a matter of discussion by researchers for many years as an alternative method to nitrogen inputs [16]. The group highlighted interseeding studies of some alfalfa species that significantly increased the total soil nitrogen, forage quality and aboveground production which was parallel with increases in SOC sequestration. This group also reported increases in SOC by 4% to 17% across three post-interseeding dates (3-, 14- and 36 years) using yellow-flowered alfalfa into a northern-mixed prairie resulting in C sequestration rates of  $1.56$ ,  $0.65$  and  $0.33 \text{ Mg C ha}^{-1}\text{yr}^{-1}$  respectively, and no evidence of increase in emissions of GHG  $\text{N}_2\text{O}$  as a result of the interseeding.

### Degraded lands restoration

Restoration of badly degraded rangelands soils (and ecosystems) that were formerly under cultivation, mining, depletion of woody vegetation and restoring soil stability with permanent vegetation is another area of management that needs urgent attention and has a high potential to sequestering soil carbon. Reports on field studies have shown that cultivation of rangeland soils have significantly reduce

SOC in the upper surface of the soil horizon when compared to native rangelands. Derner et al. [16] used the following examples where a 62% reduction in SOC in the upper 15 cm was observed over 60 years when shortgrass steppe soils were cultivated, and upon abandoning cultivation without re-establishing vegetation showed an increase 20% SOC in the upper surface after 50 years, and since these soils only contained 67% of the SOC found in native shortgrass steppe, hints to the capability of these degrade soils to sequester C. Derner et al. [16] cited an example of Post and Kwon [38] where they reported an average increase of  $0.33 \text{ Mg C ha}^{-1}\text{yr}^{-1}$  ( $299 \text{ lbs ac}^{-1} \text{ yr}^{-1}$ ).

Since most of these lands have lost a great deal of the SOC stock, the CRP is a recommended judicious land use practice that has been effective in the enhancement of SOC pool and reducing sediment load [7]. Employment of this program estimated SOC sequestration rates of  $600\text{-}1000 \text{ kg C/ha/year}$  [39], while other reports highlighted consistent increase in SOC content on ploys set aside on the grass ley system. Derner et al. [16] reported on another field study where adoption of CRP on degraded semi-arid savanna rangelands in Texas, Kansas and Nebraska resulted in a SOC sequestration rate of  $0.8 \text{ to } 1.1 \text{ Mg C ha}^{-1}\text{yr}^{-1}$  ( $725.22 \text{ to } 997.17 \text{ lbs ac}^{-1} \text{ yr}^{-1}$ ) and an average  $0.9 \text{ Mg C ha}^{-1}\text{yr}^{-1}$  from Texas to North Dakota.

Albeit a mere 2.3 M ha of the land was allowed for surface coal mining in the US between 1977 and 2001 [40], it is important to restore these soils because of the soil salvage processes (collection of the two surface profiles) that support high rates of SOC sequestration capability due to dilution of the SOC pool when SOM rich surface horizons mix with subsoil horizons consisting of lower SOM content [16]. The group explained that mined soils have a SOC sequestration potential similar to marginal, highly erodible croplands restored to grasslands. The soil quality diminishes greatly for stored mine soils since the rate of organic matter degradation/decomposition enhances, likewise increase loss of plant residue inputs and general loss of microbial functions. Increases in SOC of about 400% over a 30 year period on reclaimed mine soils (0-15 cm depth) in Wyoming.

Many reports have shown increases in soil carbon storage on marginal agricultural lands to grasslands by way of restoring some of the carbon lost via soil erosion and tillage as a result of years of soil disturbance. While plants are the main source of adding carbon to the terrestrial environment, much of the available studies focus on revegetation and vegetation manipulation of these marginal agricultural lands to grasslands and little attention is given to restoring degraded rangelands [41,42]. Removal of some invasive species (e.g. cheat grass) associated with increase fire tendency, and organic amendment (manure and compost) are consideration that may enhance soil and carbon storage respectively [24]. Again these applications are not studied at the more arid end of the spectrum, and may not be practical either.

### Soil erosion

In the US some estimated 15 MMT of soil carbon is added to the atmosphere yearly as a result of water erosion [43]. However, soil erosion also resulted from natural processes, poor grazing practices, construction, cultivation, and other management practices that reduce the net soil carbon stock to an elevated atmospheric carbon flux [24]. The extent of soil erosion is dependent on primary factors such as vegetation cover, vegetation residue, soil type, slope and precipitation that can be maneuver by monitoring grazing intensity [44]. Residual dry matter has been utilized by many natural resource protection programs as an indicator for the appropriate amount of livestock impact, since it has been found to be a key factor in retaining SOC on croplands [45].

Also, current studies on croplands indicate that erosion can function as a carbon sink in some cases [46,47].

Accelerated soil erosion is the most severe degradative process, it greatly impact the SOC pool by decreasing the biomass productivity and reduces the quality and quantity of biomass in the soil [7]. During erosion, redistribution of SOC over landscape, depressional sites and aquatic ecosystem may be released as  $\text{CO}_2$  during mineralization [7]. Better understanding of the impact of soil erosion on the SOC dynamics and C translocation is necessary so as to effectively assess the role of the erosional processes on GHGs emissions. Accelerated soil erosion is a major factor depleting SOC on deep slopes, while on flat soils with no erosional risks, mineralization usually dominates. This is supported by many field experiments where long-term SOC loss in prairie soils was due to severe soil erosion, which may account for one-half to two-thirds of the original carbon pool, while biological oxidation of soil organic matter resulted in SOC loss during the mineralization process [7]. It is recommended that implementation and adoption of effective conservation farming systems such as recommended management practices and restoration of degraded soils coupled with judicious management of soil erosion are necessary to maintain and enhance the soil carbon stock and C sequestration. More about soil erosion and interpreting indicators of rangeland health is found on the CCX website.

### Fire

Fire is generally considered an important regulator of rangeland vegetation as it tends to bring the woody plants population under control which in turn supports the growth of forbs, grasses and grass-like plants. Due to deficiency in research studies that are linked to specific ecological sites, the effect of rangeland fires on carbon stock over the long term is not entirely lucid. However, there is variation in fire characteristics, the weather, and the carbon stores that are mainly below ground. Specific vegetation state may be maintained by the use of fire, as shrub encroachment in grassland is prevented by frequent burning. Bremer and Ham [48] showed that in a tall grass prairie annual burning resulted in moderate soil carbon loss, while no decrease in soil carbon was accumulated was reported by [49]. In contrast, regular fire may also result in the removal of woody vegetation and a grassland transition followed. An example is seen when cheat grass replaced sagebrush after being eliminated in Great Basin sagebrush.

### Reforestation and afforestation

Replanting of trees that have been removed through cutting or fire is known as reforestation while planting of trees in areas that are not currently forest is referred to as afforestation; these are ecological site specific management practices that are assumed to increase carbon stocks on rangelands [50,51]. Trees are difficult to grow at xeric end of the gradients of rangelands; however, the mesic regions are known to grow broadleaf and coniferous trees. Several reports suggested that introducing or reintroducing broadleaf trees have favorable impact on carbon sequestration on rangelands seeing that they have large root systems that promote the growth of forbs and grasses beneath the canopy on some rangeland systems [50-53].

Reforestation positively impact the soil carbon stock and sequestration rate on rangelands, however, since some regions are site specific, environmental and social tradeoffs arise. Trees use large quantity of water which may reduce water availability for other vegetation, because they impact greatly the hydrological cycle and put a major limitation on plants growth, thus creating a tradeoff between

water use and carbon fixation [51,54]. They reported that soil type, species, nutrient management and the climate impact the rate and magnitude of carbon sequestration with afforestation and as such may not always positively influence the SOC pool. A study on pastures afforested with radiate pine (*Pinus radiate*) in New Zealand showed a decrease in the SOC by 15% to a depth of 12-18 cm and concluded that this practice can result in net mineralization of the SOC pool. In another study reforestation of pasture with pine resulted in a decrease in the SOC compared to pasture and eucalyptus plantation [7].

Approximately 60% of each kg of carbon fixed annually returns to the atmosphere during respiration, and transpiring trees use up to 500 kg of water for each kg carbon fixed, this is far more than 1000 times the net carbon gain [24,55]. Also, increasing the density of thick trees may also crowd out some grasses and forbs, and may not compliment grazing management practice or support shrub land or grassland habitats [24]. Therefore management practices that seek to create a balance between vegetation transitions, growth region selective for trees and shrubs and address water scarcity should be areas of relevance. In addition, visual and cultural preferences better align management practices that target promotion of wider biodiversity goals with carbon sequestration [56].

Sites where there is woody vegetation are usually drought and fire prone ecological sites, hence, there are some concerns when it comes to reforestation and afforestation since burning may result in a net carbon lost. Plantation trees such as eucalyptus are fast growing and suppress beneath canopy vegetation through shading, heavy duff and allelopathy, in addition, they are extremely vulnerable to fire. As such, characteristics of the surrounding vegetation, density of woody vegetation and the resulting fuel structure are essential and must be addressed [24].

### Soil quality and SOC

Soil affects the vegetation of rangelands since it influences water availability, soil temperature regime, elemental balance, microbial biomass carbon and the activity and species diversity of soil flora and fauna [6,7]. Enhancing the SOC concentration is very important to improving the soil physical, chemical and biological qualities. The size, shape, arrangement of solids and voids, porosity, fluid holding and retention capacity, organic and inorganic substances and ability to accommodate vigorous root growth and development describe the soil structure [57], which determines the soil quality. The soil structure

which is expressed as the degree of stability of aggregates is mediated by the SOC, biota, clay and carbonates, however, their interactions can be synergistic or disruptive to the aggregation process. Also, the SIC contributes significantly to the soil quality by increasing aggregation, especially in arid and semiarid environments. Modification of soil structure through management practices and environmental changes can increase soil carbon sequestration, agronomic productivity, fertility, enhance porosity and water quality [57].

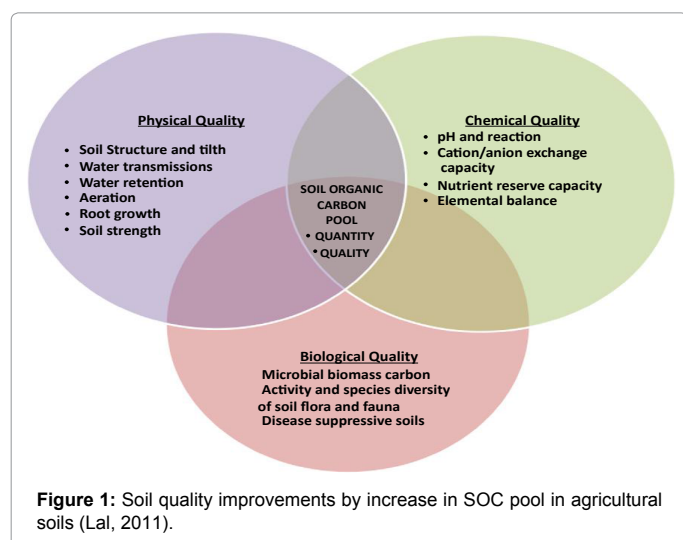
Lal [6] documented that improving soil quality can be achieved by increasing the SOC concentration in poorly managed and maintained soils, the benefits associated with management practices that target increasing the carbon stock includes (Figure 1): (i) Increase soil aggregation and aggregate stability, (ii) increase soil's cation and anion exchange capacity, (iii) reduce crusting, compaction and erosion, (iv) increase buffering capacity and moderation of elemental balance, (v) decrease in losses of soil water through increase water infiltration rate and reduction in evaporation, (vi) improvements in total and macroporosity, (vii) increase microbial biomass C, along with activity and species diversity of soil biota, and (viii) increase methane oxidation capacity, and moderating the rates of nitrification and denitrification. Favorable management practices addressing those crucial factors as well as the climatic variations can result in increased SOC concentration and agronomic productivity.

### Impact of climate change on soil organic carbon

Climate change is one of the most contending abiotic factors that impact soil quality by affecting soil aggregation through alteration in temperature regimes and soil moisture levels, which can cause reorientation of soil particles that at times may be beneficial. Aggregation is usually affected by freeze-thaw cycles in moist, temperate regions [57]. However, changes in temperature and water availability impact the decomposition rates of microbial and biotic activity and species composition in the ecosystem [7,57]. Climatic changes can alter the biomass return to the soil since temperature and moisture changes may affect SOC pool and the physical properties of the soil [7]. Increase respiration and biological activity resulted at warmer temperatures and higher standing stock of SOC at lower temperatures, while frigid and wet soils usually have less available SOC compared to warm and dry soil [57].

Lal [7] documented that a decrease in effective precipitation with increase temperature may cause a decline in the net primary productivity in some regions of the tropics while increasing it in the boreal forest regions. It is estimated that an increase in the average yearly temperature by 1°C is equivalent to a pole ward shift in the vegetation zones by about 200 km, even though the initial effects may be subtle [58,59]. The rate of mineralization is exacerbated with increase temperatures resulting in a decrease in the SOC pool and increasing tendency for erosion. Also regions that are carbon sinks could possible become net carbon sources as a result of the projected temperature increase.

Lal [7] highlighted a study on the impact of climate change on the Mediterranean basin that predicted an average altitudinal shift in the vegetation belt of 500 m with a 3°C rise in temperature. They reported that temperature increases would deplete the SOC pool by 28% in the upper layers in the humid zone, 20% in the sub-humid zone and 15% in the arid zone. In another study, Cheddadi et al. [60] predicted that an increase in the atmospheric CO<sub>2</sub> to 500 ppmv with a correlating temperature increase by 2°C parallel with a reduction in precipitation by 30% could significantly change the Mediterranean vegetation. Rosenzweig and Hillel [61] also provided a comprehensive



review on the impact of climate change on biomass and agronomic production in different ecoregions that could improve the knowledge and understanding of rangelands and climate variations.

Limited rainfall can cause the soil to undergo frequent changes in the moisture regime, resulting in wet-dry cycles that are influenced mainly by the climatic factors. The variation in moisture levels and wet-dry cycles impact soil aggregation by disrupting the swelling clays and only positively impact the soil in the initial stages. Wetting causes clay particles to breakdown, form bridges and coatings while drying [62], thus, decreasing aggregate stability as a result of comminution [63]. Several studies have shown that wet-dry cycles affect the porosity and quantity of POM incorporated into soil aggregates and are crucial in aggregation in soils of arid, semiarid and sub-humid regions [57]. Increase aggregate stability on arid environments can be achieved through factors such as crusting, carbonates, and earthworms; crusting reduces detachment and erosion. Some arid environments soils have increased levels of aggregation and stable micro-aggregation than soils in humid areas (Mediterranean) [57].

Some reports have suggested that management practices such as irrigation; mulching and cover cropping can modify temperature and moisture regimes and moderate the impact of the wet-dry cycles. No-till soils would be exposed to less severe wet-dry cycles due to surface residue protection while amendment of soil with humic substances can reduce slaking or soil breakdown [57].

### Soil moisture

Several reports have shown that soil water flow, availability and storage is influenced mainly by the soil structure and texture [57]. The movement of water deeper into soil horizons, increased leaching, improved infiltration and reduced runoff can be achieved when the bypass flow in soil is increased, which is incumbent on the aggregation and the interconnected pores [57]. Nissen and Wander [64] added that water stress in arid conditions could be contributed to by reduced matrix flow. Soil moisture is a very important health parameter on rangelands, especially on arid and semi-arid environments where it is the primary limiting factor. The effect of animal and the period of grazing (i.e., the spatio-temporal impacts) can also account for some of the variations seen in soil moisture, hence, management decisions could impact positively on soil moisture [65].

The SOC pools of the North American Great Plain rangelands have shown increases to a depth of 30 cm with increasing precipitation. However, a report has shown that lower SOC pools, greater root C/soil C ratios and induced-grazing compositional shift to greater C4 dominance in the semi-arid shortgrass steppe of the Great Plains with respect to grazing were thought to be the reasons for the difference in SOC between the semi-arid and mesic rangelands [16]. The authors further elucidated that the changes in species composition as a result of induced-grazing with respect to changes in soil C in shortgrass steppe were due to magnitude and proportion of fine roots mass in the upper soil horizon [16].

In another field study a negative relationship between C sequestration and mean annual precipitation was observed for the 0-10 cm and 0-30 cm depths of the soil profile across stocking rates [16]. Approximate 440 mm and 600 mm precipitation for the 0-10 cm and 0-30 cm soil depths respectively was the threshold values from which positive to negative C change took place. C sequestration did not increase above these threshold precipitation values and assumed to possibly decrease the SOC [16]. Also in another report, nine long-term grazed and ungrazed

(20-71 years) sites along a semi-mesic precipitation gradient (330-480 mm) in Canada showed no differences for SOC [66]. Authors reasoned that the effect of precipitation on nitrogen turnover and availability may be the controlling factor for transition in C sequestration on semi-arid to mesic environments and the apparent reduction in C sequestration in wet regions is thought to be as result of increased microbial biomass C and N and continuous break down of organic matter resulting in increased nutrient cycling [16].

### Nutrient management

Judicious nutrient management practice is crucial to rangelands soil for C sequestration. The SOC concentration increases to a greater extent with the application of organic manures and compost (integrated nutrient management) than the same quantity of nutrients of commercial inorganic fertilizers [67]. The quantity of humic substances and biomass carbon produced or returned to the soil is dependent on the effects of the fertilizer used, thusly the SOC pool is influenced thereof. This therefore means prudent supply of nutrients (such as nitrates, phosphates and other essential nutrients) must be in balance in the soil so as to enhance the biomass production to appreciable levels that can mitigate elevated atmospheric CO<sub>2</sub>.

Lal [7] reported from the literatures that increase in SOC concentration can be achieved with long term manure applications, which may also improve soil particle aggregation. He noted that soils that are amended with organic manures are better able to sequester carbon with the application of conservation tillage for longer time. Only 54% of the 820 MMT of manure produced in Europe yearly is being applied to arable lands, yet, it is documented that 100% incorporation of the said manure into arable lands in the European Union could achieve a net sequestration of 6.8 Tg C/year which could mitigate about 0.8% of the 1990 CO<sub>2</sub>-C emission for the region [68].

### Technological Synthesis

#### Deep root plant breeding

Active agricultural intervention could further intensify C sequestration to deeper depths through breeding of plants with improved and deeper rooting habits and architectures on rangelands. The soil structure and its steady-state carbon, nutrient and water retention, as well as sustainable production could be improved with breeding of plants with bushy and deeper root systems [69]. Kell [69] reported that breeding strategy can sequester carbon in a steady-state by increasing the rooting depths of grasses and crop plants, but found this to be dependent mainly on its lifetime in different molecular forms in the soil.

It is of the view of a few others that the physico-chemical properties of the soil entirely control root depths and as such breeding of plants with improve root depths or application of genetics might not achieve C sequestration on agricultural lands [69], however, experimental findings oppose this idea [70,71], also several simple gene-base arguments nullify the view. Kell [69] highlighted the findings for two studies; an experiment with same soil but different organisms showed a significant variation in the plant root depths while in another study different cultivars of the same plant in the same soils or growth media revealed plant root depths with a great deal of variation.

Smith [72] reported that increasing the root depths can potentially achieve C sequestration of 0.3- 0.8 Mg C ha<sup>-1</sup>, even though this is a small amount it would be beneficial to the SOC pool just by adding to the sink capacity. Also Lal [7] outlined that the soil once sequestered this



reasonable and conservative amount of carbons, and just by doubling the root steady-state depth for 1 m to 2 m can extract substantial amount of CO<sub>2</sub> from the atmosphere [69]. Rangeland management can seek to incorporate this technology in semi-arid and arid environments to increase C sequestration and improve carbon stock and soil quality.

### Root architecture

The literature has a wealth of articles describing many mutated architectural genes that are responsible for root hair formation, root length, root branching, etc; however, at present there is similarly limited knowledge about the effect of mutations on their characteristics and mode of actions by which they impact the phenotype [69]. Root architecture is also governed by hormonal behaviors from soil organisms and the host plant, and to a lesser extent the physico-chemical environment [73,74].

### Rooting depth

Kell [69] highlighted several articles that present considerable opportunities to increase the rooting depth of plant types or cultivars by employing the appropriate breeding strategies. Very importantly, at present there are cultivated agricultural crops that have root system extensions not much beyond 1 m whereas many do hinting to the possibility of breeding this trait [69].

Root length is a customary function of aridity, for example phreatophytes [75], some common long-rooted plants are common to arid regions, albeit this trait mainly relates to the ability to obtain water from deep sources. The idea of whether plants extract water from the soil or add it (hydraulic redistribution) i.e. the root-water-soil dynamics is not fathom [76]. There are supporting evidence that deep root plays a key role in C sequestration [69], soil structural improvement [77], hydrology improvement [78] and improving agronomic productivity due to increase SOC [79].

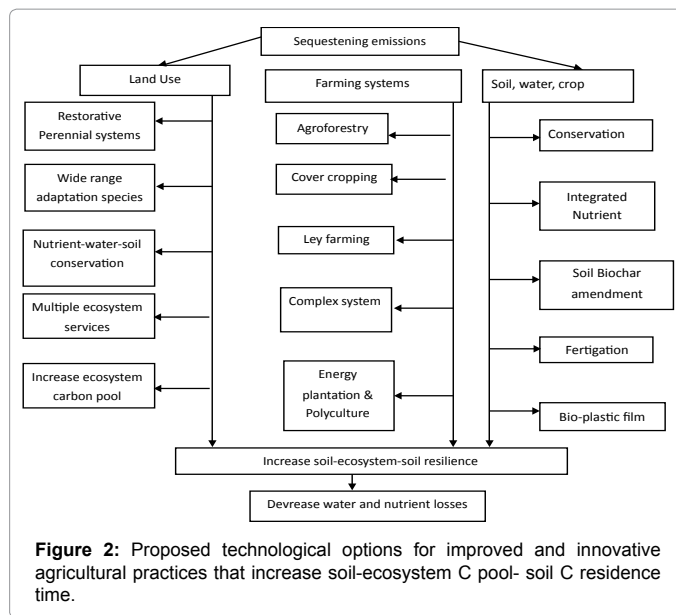
Kell reviewed studies that documented improved root architecture and plant yield with the application of quantitative trait loci (QTLs), and a number of other plants such as *Panicum virgatum* (switch grass), vetiver (*Chrysopogon zizanioides* L.) and grasses that significantly contribute to C sequestration due to their below-ground biomass. Also there have been at least five widely cultivated crop plants can produce roots beyond 2 m.

### Perenniality

Perennials per se typically develop remarkably longer roots than modern domesticated annual crops [80,81], they are model plants to prevent nitrogen runoff [82] and sequester substantial amount of carbon in soil [83]. Perenniality and large root architectures can be separated or coupled for rangeland purposes yet remain uncertainties. However, conservation of flowering times genes between monocots and dicots seem to contribute to perenniality [84,85] unlike root architecture.

### Recommended management practices

Adoption of RMPs coupled with land use change can be a very important technological tool for SOC sequestration [7], and every effort should support the application on rangelands. Restoration of degraded lands and ecosystems, conversion of marginal agricultural soils to restorative lands use and perennial vegetation with the adoption of site-specific RMPs can greatly improve the sink capacity of SOC [7]. Implementation of RMPs prevent tillage-induced soil disturbances, minimizes soil erosion, conserve soil water and return large quantities of root and above-ground biomass to the soil [7]. Crop residues and



**Figure 2:** Proposed technological options for improved and innovative agricultural practices that increase soil-ecosystem C pool- soil C residence time.

biosolids increase the C input and SOC stock [86], conjointly Graham et al. [87] added that biosolids inputs in the surface layer increases SOC. Management of agriculture lands along with the adoption of RMPs has resulted in SOC sequestration through aggregation, humification, translocation in the sub-soil and formation of secondary carbonates [7].

### Agricultural practices proposal

According to Meinhausen et al. [88], to mitigate global temperature rise to 2°C sustainable management of soils of agroecosystems is necessary. The group proposed a technological option (Figure 2) that will aim at improving and innovating agricultural practices that target reduction of gaseous emissions through soil-water-crop management and sequestration emissions by way of land use, farming systems and soil-water-crop management that could result in the reduction of input by half while doubling the productivity and enhancing the soil-ecosystem-social resilience. There is much to be extracted from this technological synthesis for rangeland ecosystem management for increasing the SOC pool and improving soil quality and resilience.

The proposed synthesis for sequestering emissions involves judicious land use, application of appropriate farming systems and management of soil-water-crop, which would results in increase soil, ecosystem and social resilience. Land use through implementation of restorative perennial systems, introduction of species with wide adoption capability, application multiple ecosystem services, conservation of soil, water and nutrients; cover cropping and mulching, ley farming, agroforestry and energy plantation and polyculture are some farming systems proposed; while soil-water-crop management can be achieved through conservation tillage, integrated nutrient management (manure, compost, biological nitrogen fixation, biofertilizer), fertigation, bio-plastic film and soil amendments (e.g. biochar) technologies and is prescribed to increase the soil, ecosystem C pools and their residence time (Figure 2) [6].

### Soil amendment- Biochar

Soil biochar amendment is another proposed technological option for increasing SOC pool [89,90]. Biochar is formed from low temperature pyrolysis of biomass in the absence of oxygen to produce charcoal. Sohi et al. [91] reported that soil biochar amendment may

sequester 1 billion tons C/yr or more [92]. The literature provided a handful of long term field-based studies that give some reliable data on C sequestration through the application of biochar (2-5 tons ha<sup>-1</sup>) on grazing and croplands [6].

Lin [90] reported that yard trimming, tree leaves and forest litter are possible feedstock sources to produce biochar but the feedstock source can impact the properties and quality of the biochar obtained, thus, organic waste-based biochar is recommended as it showed high carbon stability, increase soil alkalinity along with excellent water and nutrient holding capacities. Others support the use of soil biochar amendment once it does not involve removal biomass that protect soil surface [14,91,92]. In a field study on soil amended with biochar that was exposed to weathering conditions, the SOC of the soil remained constant throughout the 12 month period hinting to the stability of biochar in amended soil systems [90]. Lin [90] also added that biochar incorporation into top cropland soils can permanently sequester average 98 ton C ha<sup>-1</sup> from the atmosphere via photosynthesis and pyrolysis while reducing the application of chemical fertilizers.

## Challenges

The review uncovered some factors that create limitations for rangelands (and other agroecosystems) to sequester carbon at reasonable levels that would make them functionally fulfilling their C sink capacity. It is evident that more research and development priorities is needed to address rangeland ecological dynamics so that there will be better understanding of the ecological sites and the link to 'best fit' ecological models since management in of itself will not reliably increase carbon sequestration especially along the semi-arid and arid gradients of rangelands [24]. Also, management strategies to incorporate protection of carbon stocks already present in soils and rangelands conversion from intensive land use are still limited [24].

There is very little intuitive understanding of the fundamental and functional processes and mechanisms that affect SOC dynamics under normal and varying precipitation patterns on semi-arid and arid ecosystems of rangelands; for example the microbial function and processes, how they are impacted by land management, environment and interactions need to be explored [16]. A controlling factor that affects nutrient cycling (cost and benefits) in the ecosystem is management-environment interactions that if addressed can provide better understanding of climate-plant-soil-microbial interactions when coupled with prescribed land management practices (grazing management) [16].

The CCX voluntary carbon market was abandoned in 2010 [29] because of a number of inconsiderable but very important factors such as insufficient understanding of the C sequestration process on rangelands [30,31], difficulty of sequestering carbon at the arid sites [16], low carbon prices, prediction of the effects of a national carbon tax by the global nature of beef production, the legality of enrolling state-owned lands [26], some ranchers were skeptic of the potentially intrusive obligations and liabilities associated with the carbon market, the motivations behind the notion of climate change and the feeling that the traders, speculators and middlemen would be the ones making the real money [25]. In addition, incentives for enrolling rangelands in mitigation projects were not financially attractive and environmentally proactive in regards to increasing and conserving SOC stocks [24,25].

Lal pointed out that there are concerns about the residence time of carbon sequestered in the soil owing to the projected climate change and increasing anthropogenic activities such as urbanization,

desertification and deforestation and the relevant processes of soil C sequestration (e.g., aggregation, humification and secondary carbonate formation). There are also questions about the possibility of establishing saturation of terrestrial C sink capacity of the world soil too soon, since desertification and soil degradation seem to be happening at a faster rate than soil management or land restoration [6]. Also adoption of RMPs is soil-specific; hence, the soil and biome required developed and validated site-specific technologies, and there is also the need to carry out analysis of the life cycle of RMPs at farms, watersheds, and regional scales so as to assess the net SOC gains due to the concealed C cost associated with RMPs [6].

Breeding plants with deeper root systems can do a lot for carbon sequestration and improving soil quality, however, more study on roots interactions with the soil micro-organisms and invertebrates is found wanting, the genes that are responsible for root development, as well as the effects of the biochemical turnover associated with deeper root plants are still outstanding [69].

## Opportunities

The growing interest to find the most appropriate and site-specific land management practices that will seek to increase terrestrial carbon stocks on rangelands can possibly modify government natural resource conservation programs as well as the carbon market policies if it should be re-initiated in the future. Although carbon sequestration on rangeland is a not a permanent solution to the increasing atmospheric CO<sub>2</sub>, it can extract appreciable amounts, improve the soil quality and resilience and buy us time until an alternative solution to fossil fuel is developed and implemented [7,16].

Carbon sequestration on rangelands is environmentally friendly, inexpensive and natural process of mitigating climate change when compared to other methods, unlike others, the co-benefits of increasing the SOC pool includes improving biodiversity, enhance agronomic productivity, reduce erosional losses, restore degraded lands, improve the quantity and quality of water resources and advance global food security [6].

The carbon credit market was projected to reach \$500 billion in trading by 2020; however, it is believed that with developed policies along with accurate, credible and cost-effective protocols that better reflect rangeland dynamics and the aim of the carbon market, educating ranchers about the carbon sequestration process and increasing the carbon credit prices would make rangeland projects sustainable and successful [25]. The Trigg family was successful in increasing the carbon stocks on some rugged rangelands by transitioning the land to more sustainable, carbon-oriented forms of ranching and was one of the few to earn an income from selling the carbon credits and as such, insight can be garnered from the experience if future carbon markets should re-initiated [29].

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