Chapter

Soil Carbon Storage Potential of Tropical Grasses: A Review

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Abstract

Environmental degradation and climate change are key current threats to world agriculture and food security and human–induced changes have been significant driving forces of this global environmental change. An important component is land degradation which results in a diminished soil organic carbon (SOC) stock with concomitant loss of soil condition and function. Land management to improve soil organic matter content, condition and productivity is therefore a key strategy to safeguard agricultural production, food supply and environmental quality. Soil organic carbon sequestration through the use of plant species with high photosynthetic efficiency, deep roots and high biomass production is one important strategy to achieve this. Tropical pastures, which are adapted to a wide range of environmental conditions have particular potential in this regard and have been used extensively for land rehabilitation. Tropical pastures also have advantages over trees for biomass and carbon accumulation due to their rapid establishment, suitability for annual harvest, continual and rapid growth rates. In addition, tropical pastures have the potential for SOC storage in subsoil horizons due to their deep root systems and can be used as biomass energy crops, which could further promote their use as a climate change mitigation option. Here we aimed to review current knowledge regarding the SOC storage potential of tropical grasses worldwide and identified knowledge gaps and current research needs for the use of tropical grasses in agricultural production system.

Keywords: Soil organic carbon, Tropical perennial grass, climate change mitigation

1. Introduction

Environmental degradation and climate change are key current threats to world agriculture and food security [1–5]. Human–induced changes to land cover have been significant driving forces of this global environmental change, of which, soil degradation resulting from land conversion, agricultural intensification, soil disturbance and increased erosion have been key factors [6–9]. An important component of this land degradation globally has been a diminished SOC stock with concomitant loss of soil condition and function, compromising food production and agricultural sustainability [10–12]. Land and soil management to increase soil organic matter content, soil condition and productivity is therefore a key need globally to safeguard agricultural production, food supply and environmental quality.

Organic carbon in soils globally is estimated to be between 1500 and 1600 Gt [13, 14] to 1.0 m depth which represents a significant component of the global carbon cycle, storing more carbon than is contained in vegetation and the atmosphere combined [15–17]. It has been estimated that, worldwide, soils have lost between 42 and 78 Gt of their original SOC as a result of management pressures [18]. With this carbon depletion, however, comes a significant opportunity, since soils are believed to have the capacity to store an additional 0.4–1.2 Gt C $year^{-1}$ with the introduction of more judicious land management practices [3, 7, 19–22]. As such, soils globally have considerable potential to offset greenhouse gas (GHG) emissions and SOC storage has been widely promoted as an important strategy to help meet national and international emissions reduction targets [23]. Additional SOC storage might therefore have the dual benefit of contributing to our response to climate change globally whilst helping to restore soil condition and function to promote sustainable land management, improved production and productivity [3, 7, 19, 20, 24].

Methodologies and management practices that reduce SOC loss or promote the storage of additional soil carbon are being actively investigated globally. It has been widely reported that cultivation accelerates organic matter decomposition by exposing sites within soil aggregates that were previously protected [25–29] while soil erosion, vegetation clearing and removal of crop residue are also known to result in long–term soil carbon loss [30, 31]. However, there are management practices which seem to either arrest SOC loss (e.*G. minimum* tillage) or to promote carbon storage such as afforestation, pasture conversion, grazing management, cover crops, water harvesting, erosion control and the use of soil amendments including biochar [32]. Not all of these are practical in production landscapes globally and not all will be equally effective in the management of SOC. The effectiveness of various management practices is therefore being explored to facilitate optimum carbon storage that can be integrated with agricultural production systems.

An approach that has attracted particular attention is the use of perennial grass species within the production system, which appear to significantly increase SOC across a range of environments and this is particularly true where these perennial grasses replace cropping systems [33–36]. Pastures are varied in terms of their geographical distribution and species composition comprising native and exotic, annual and perennial grasses, legumes, herbs and shrubs [37]. They are the primary resource for many farm industries and are the basis for the production of meat, wool, milk and fodder. Schuman et al. [38] estimated the SOC under grazing lands of the world to be 10–30% of the total global SOC stock, while Janssens et al. [39] estimated the overall C sink in grassland soils of most European countries to average approximately 60 g C m^{-2} $year^{-1}$.

Tropical perennial grass species have been particularly promoted due to the high biomass and carbon accumulation resulting from their excellent photosynthetic efficiency, rapid establishment, fast growth, deep root systems and potential annual harvest [28, 40, 41] and Parton et al. [42] suggested that tropical grasses have significant potential as a carbon sink. However, there is a research need to fully quantify their capacity to store additional soil carbon relative to other management systems and hence, their potential for greenhouse gas (GHG) abatement and soil condition recovery [43–45].

Here we aimed to review current knowledge with regard to the SOC storage potential of tropical grasses worldwide given their wide distribution and extensive use, where current agricultural policy environments have identified land management innovations as key entry point to achieve co-benefits of resilient agriculture, poverty alleviation, and climate change mitigation. Hence, we identify knowledge gaps and current research needs to fully explore the potential of tropical grass species for SOC change.

2. SOC storage potential of tropical grasses

A number of studies have considered the soil carbon storage potential of tropical pastures by comparison with other management systems. An empirical, five year study of tropical ecosystems in South America by Amézquita et al. [46], demonstrated that although tropical pastures were second only to native forest in the quantity of SOC stored, organic carbon in the soils of these pasture systems represented a higher proportion (95–98%) of the total ecosystem carbon than comparable native tropical forest systems and silvo–pastoral systems. Desjardins et al. [47], reported that where tropical forest was converted to tropical pasture in Brazilian Amazonia, a slight increase in SOC content occurred in both sandy and clay soils while Post and Kwon [48] described the similarity of the average rates of SOC accumulation in forest and grasslands of 33.8 and 33.2 g C m^{-2} y^{-1}, respectively through time following management although above ground carbon is lost. In Australia, Chan and McCoy [43] also identified the potential of introduced perennial pasture (Kikuyu) to store a mean of 73 Mg C ha^{-1} in soil which was similar to soils under native trees (77 Mg ha^{-1}). Under some circumstances, tropical pastures have been reported to have a greater capacity to store SOC compared with trees or forest. For example,

Grass type	Age (Year)	Sampling depth (cm)	Mg C ha^{-1} yr^{-1}	Mg C ha^{-1}	Country/ region	Source
African grass	—	—	8.67	—	Latin America	[50]
Andropogon guyanus		0–100	14.45	—	Latin America	[50, 51]
Brachiaria dictyoneura	3.5	—	8.57	30	Latin America	[52]
Lemongrass	—	0–30	3.08	—	India	[53]
“	—	0–30	5.38	—	India	[54]
Palmarosa	—	0–30	2.79	—	India	[53]
“	—	0–30	6.14	—	India	[54]
Kikuyu	3	0–10	2.6	34 g (kg^{-1})	Australia	[55]
“	15	0–20	—	67.2	Australia	[43]
“	—	0–30	0.9	—	West Australia	[56, 57]
“	—	0–30	0.26	—	South Australia	[56, 57]
Miscanthus	10	0–80	0.78	—	Europe	[58]
“	2.5	0–30	0.73	1.82	UK	[59]
“	2.5	0–30	0.87	2.17	UK	[59]
Vetiver	5	0–30	5.54	—	India	[53, 54]
“	7	0–30	1.61%		Ethiopia	[60]

Table 1.
Total soil carbon stored under different tropical grasses with different soil sampling depth and age of plantation.

Guo et al. [49], reported 15–20% larger soil C stocks under native pasture compared with a 16 year old pine plantation to 1.0 m in the soil profile. These findings seem to be convincing, although some caution must be attached to many such results given that they typically do not account for above-ground biomass and are rarely reported on an equivalent mass basis. There is nevertheless, growing evidence that tropical pastures might have the capacity to store SOC that is at least equivalent to that of forest systems in terms of rate and quantity of accumulation. However, the quantity and rate of carbon accumulation would appear to be moderated by environmental conditions and both preceding and ongoing management practices. Consideration and knowledge of the behavior and potential carbon storage of particular tropical grass species has much to add to this debate.

Some specific tropical grass species (**Table 1**) such as *Andropogon guyanus* (gamba grass, Rhodesian bluegrass, tambuki grass), Lemongrass (*Cymbopogon citratus*), Palmarosa (*Cymbopogon martinii*), Kikuyu (*Pennisetum clandestinum*); Miscanthus (*M. giganteus*), Vetiver (*Chrysopogon zizanioides*) have been highlighted for improving soil carbon storage potential even though their efficiency is determined by a range of environmental and management factors [46, 60–64]. However, Fearnside and Barbosa [62], found that management practices could on the other hand determine whether tropical pasture soils could be net sinks or sources of carbon, demonstrating in Brazilian Amazonia, that under "typical" (without inputs or other practices) and "ideal" (with variety of appropriate practices) management, tropical pasture soils were a net carbon source releasing an average of 12 Mg C ha^{-1} following deforestation.

3. Processes of SOC storage

The process by which organic carbon stored in soils follows various pathways such as roots, root exudates and litter (both above- and below-ground). Plant litter consists of dead roots, is a primary source of soil organic matter which is the largest terrestrial pool of carbon [65]. Despite, often considered separate processes of litter decomposition and soil organic matter stabilization is an important control of carbon storage and SOC dynamics [66, 67]. Decomposition of plant litter is one of the main processes driving nutrient and carbon (C) cycling in terrestrial ecosystems [68]. The effect of litter quality on SOM stabilization is inconsistent and litter addition promotes SOC mineralization, but this promotion alters by soil moisture and litter type [69]. Hence, understanding the interactions between the initial composition and subsequent decomposition of plant litter help to understand the flow of organic matter between soil carbon pools [70]. Root exudates are also one of the various pathways through which the carbons fixed released into soils [71]. Plants release a part of their metabolome into soils and thereby provide information about the potential biological function of exudates in the rhizosphere [72].

Root biomass production is an important plant component that can contribute to soil carbon sequestration. A strong fibrous root system, penetrating deep into the soil profile and growing vertically rather than horizontally, is therefore desirable to maximize soil carbon sequestration. Hence, the large root systems of tropical grasses might potentially facilitate long term deep carbon storage and reduce the chance of decomposition and carbon loss [44]. For example, the roots of vetiver grass have been found to contribute significantly more to additional SOC storage than those of other grass species [60, 63, 73]. Although the extent of SOC sequestration potential of tropical grass species still requires further research, they would appear to have particular promise with regard to soil carbon storage compared with other species.

Due to their large biomass production and their extensive and fast growing root system, tropical perennial grasses would seem to have the capacity to rapidly store or contribute large quantities of carbon in addition to their other varied uses [53, 74]. Deep rooted tropical perennial grasses have been identified as the most promising plants that could contribute to SOC storage and thus climate change mitigation [44, 75–78]. Awoke [79] highlighted further the potential of tropical grasses for both above- and below-ground C sequestration by planting strategically on appropriate lands.

Most of studies relating to tropical grasses to date have focused on the actual biomass production potential. However, there are only few studies which have considered the actual net accumulation of carbon stored in the soil under tropical grasses (**Table 1**) highlighting the need for controlled studies to determine not only biomass and inputs but also the net effect of tropical perennial grasses in terms of carbon storage and the mechanisms, stability and longevity of the carbon stored such as the rate of new carbon turnover and carbon cycling of the newly added carbon and the extent to which it is retained in the soil system.

4. Effect of cropland conversion to tropical pastures on soil carbon

Cropland conversion to pastures has recently become a common practice and is believed to have considerable potential to store significant quantities of additional SOC [19, 38, 80]. For example, Conant et al. [33] and Conant [81], reviewed studies worldwide and concluded that cropland conversion to grasslands can create a significant carbon sink, with a mean 5% annual increase in SOC. In the mid–western United States, agricultural land conversion to perennial grassland showed a constant rate of 62 g C m^{-2} $year^{-1}$ SOC accumulation over 40 years in the top 10 cm [82]. Similarly, Abberton et al. [83] reported that, in temperate regions, most grasslands can be considered soil carbon sinks of up to 40 g C m^{-2} $year^{-1}$ following cropland conversion. Post and Kwon [48], further estimated that land use change from cropping to grassland could result in an increase of 33.2 g soil C m^{-2} $year^{-1}$ in the USA. While a meta–analysis in temperate grasslands showed that at the 0–30 cm soil depth over 20 years SOC sequestration reached 44 g C m^{-2} $year^{-1}$ which is half of the rate (95 g C m^{-2} $year^{-1}$) at which SOC is lost over a 20 year period following permanent grassland conversion to an annual crop [84]. These estimates suggest that SOC recovery is possible but is usually slower than initial loss. Research in the south eastern United States also suggested up to 100 g C m^{-2} $year^{-1}$ could be sequestered in soil following conversion of cropland into optimally grazed pastures (where the available pasture matches the animal needs). These increases have been attributed to the fast growth habit of pastures, negligible erosion and the minimal disturbance to soil compared to cropping [28]. Although focused principally on temperate grass pasture species, these studies demonstrate the potential increase of SOC as a result of cropland conversion to grasslands.

5. Form and resilience of carbon stored under tropical grasses

Many of tropical pasture species have a distinctive carbon fixing (photosynthesis) pathway and are referred to as C_4 plants [43]. All plant species have the more primitive C_3 pathway, described by the Calvin Cycle [85] but an additional C_4 pathway evolved in species in the wet and dry tropics. C_4 pastures are those that have the photosynthetic processes divided between mesophyll and bundle sheath cells that are anatomically and biochemically separate, while C_3 pastures are those which use only the Calvin cycle photosynthesis pathway for fixing CO_2 which takes place inside of the chloroplast in mesophyll cells [86, 87].

In terms of photosynthetic efficiency, C_4 grasses are approximately 50% more efficient than C_3 plants as a result of this distinctive carbon fixation mechanism [88]. Wang et al. [87], indicated that more efficient use of light and CO_2 in C_4 plants results in an increase in both biomass production and CO_2 fixation. Hence, as a result of their high photosynthetic efficiency and productivity, tropical C_4 grasses might be expected to have larger potential for SOC sequestration compared with temperate and annual pastures [55]. Most tropical pastures are important perennials and provide a permanent soil cover and thus prevent soil surface erosion [89], which is of particular importance in the prevention of SOC loss by erosion. Greenland [90] hypothesized that, with suitable management practices, tropical grasses could have a significant potential as a soil carbon sink. Our knowledge of perennial tropical species growth, interaction with the soil, potential quantities and mechanisms of carbon storage remains incomplete [50].

It has been speculated that carbon storage in sub–soils might be an important mechanism leading to increased SOC storage in soils [44, 77] and it is known that tropical grasses translocate large quantities of carbon to their root systems [44]. This suggests an effective translocation to deeper soil layers where soil carbon is typically more protected from decomposition processes [91–94]. Accumulation of carbon in deeper soil layers might therefore be an important mechanism for carbon storage under this vegetation type [59, 89, 95]. The deep rootedness of tropical pastures might, therefore, potentially play an important role in transporting carbon to deeper soil layers and therefore facilitate SOC storage. Indeed, Fisher et al. [52], estimated that the introduction of deep rooted African grass pastures in Colombia might account for the sequestration of 100–507 Mt. soil carbon year^{-1} if their study sites were indeed representative of similar pastures throughout South America. These studies indicate the potential benefits of introducing deep rooted tropical perennial grasses for SOC storage but also the need for further carbon inventory.

6. Factors affecting SOC sequestration

Tropical pastures grow continually year round and are adapted to a wide range of soil and climate conditions because of the close interaction between climate factors and soil properties [28, 96]. In addition to soil type, management and site history could be important factors determining the direction and magnitude of change in soil carbon stock [28]. Similarly Chan and McCoy [43], indicated the higher effectiveness of pastures in increasing SOC storage under appropriate management. Wilson and Lonergan [97], also demonstrated in Australia that native and improved pastures in this environment had the same SOC quantity and that historical and contemporary management practice is a key factor influencing net SOC. The management of tropical pastures is therefore a critical determinant of whether the soils under this land use will represent a source or a sink of atmospheric carbon [62]. Poor pasture management such as over grazing, frequent burning and conversion to cultivated agricultural land could result in degradation and low productivity which can reverse the carbon sequestration potential of tropical pastures leading to carbon loss by erosion and oxidation [98]. Hence, the effects of tropical pastures on soil carbon are likely to vary because of environmental and management factors. For example Dalal et al. [99], demonstrated historical management as a key driver of SOC stock particularly in the surface soil layers. Therefore, there is a need for controlled studies that measure soil carbon with some certainty of the effects of both environmental and management factors.

Clay soils in general play a greater role to slow the rate of decomposition, due to both physical and chemical protection of SOC and typically promote larger soil carbon concentrations compared with sandy soils due to these SOC stabilization processes [100–102]. Similarly, a water saturated soil might have lower rates of organic matter breakdown because of a lack of oxygen for soil organisms compared to soils exposed to the atmosphere. Therefore, soil improvement and adding essential inputs are important to increase the rate of organic carbon addition and pasture production [28]. In addition, McKenzie and Mason [28], indicated that deep soil profiles with fertile subsoil allow deep root penetration into subsoil which is much cooler (less likely to promote decomposition) than the topsoil. Hence, maximizing the carbon input by increasing the net primary production through nutrient addition, increased nutrient and water use efficiency and minimizing the rate of organic matter decomposition after deposition in soil are important factors which can help to increase the amount of carbon sequestered from the atmosphere [96].

Carbon accumulation in pasture lands can also be determined by the length of time the land remains under pasture [64]. Hence, regardless of technologies or mechanisms, the length of time must also be taken into account when considering long–term carbon storage. Bouman et al. [103], stated that, due to various economic and biophysical dimensions, sustainability of tropical pastures can also be affected by the pasture type, age, and management which in turn can affect the carbon accumulation. Hence, McDermot and Elavarthi [104], recommended that best management practices, site specific policies and using technological options can offer good opportunities to generate positive effects on soil carbon accumulation by using tropical grasses.

Therefore, factors such as input versus outputs, climatic conditions, soil type and properties, land use control, management practices are the factors affecting SOC storage. Whenever there is a vegetation cover change from C_3 to C_4 plants, the ratio of stable carbon isotopes ($\delta^{13}C$) can be used to track changes in SOC between the C_3 and C_4 plants and the quantity of "new" carbon added [99, 105, 106]. The use of stable isotopes offers a useful quantitative technique to allow the estimation of organic carbon storage and turnover in soils, even when TOC changes are of limited magnitude [107].

7. Opportunities and economic benefits of tropical pastures

Biomass energy is currently receiving considerable attention in response to climate change and ever-increasing global energy demand [108–111] and tropical pastures would appear to have potential for the production of biofuels. For example, Clifton-Brown et al. [40], suggested that *Miscanthus* which is known for its high biomass production has value as a potential biofuel and the area over which it grows could therefore be expanded significantly throughout Europe. *Miscanthus* is grown in many European countries such as Austria, Denmark, France, Germany, Hungary, Poland, Switzerland and the United Kingdom. In France for instance, *Miscanthus* cultivation has increased since the first plantation in 2006 [112]. The EU Biofuel directive promotes the expansion of biofuels and *Miscanthus* particularly as a biomass energy source [113]. Hence, growing biomass energy crops (mainly tropical perennial grasses) specially in Europe is becoming common and expanding to consider for potential soil carbon storage and this needs to be explored further even in other parts of the world and using other different potential grasses.

8. Conclusion

Tropical pastures are potential candidates to contribute to climate change mitigation efforts through additional SOC storage due to their high biomass production, fast growth rates, and deep root systems. Using tropical grasses has also a low cost of implementation to rehabilitate degraded lands and improve soil productivity through increasing SOC. The existing literature on tropical grasses potential for soil carbon sequestration provides positive indications that significant soil carbon storage is possible. However, a number of further investigations are required to provide a sound basis on which management decisions involving tropical grasses can be made. We therefore recommend the following priority research actions to provide the required information:

- Cropland conversion to tropical perennial pastures and its potential to achieve multiple outcomes including soil health, soil security and sustainability in addition to soil carbon storage.

- A range of tropical grass species should be assessed to determine their potential to store additional carbon under specific climatic and management conditions.

- There is a need to assess the processes and mechanisms of SOC storage in deeper soil profiles under tropical perennial grasses to provide accurate estimates of SOC stocks.

- The rate of soil carbon turnover and cycling of the new carbon added and the extent to which it is retained in the soil system needs to be fully quantified.

- Best management practices, site specific policies and technological options which can positively affect soil carbon storage should be identified and clearly defined.

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