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From current stock estimates to sequestration potential

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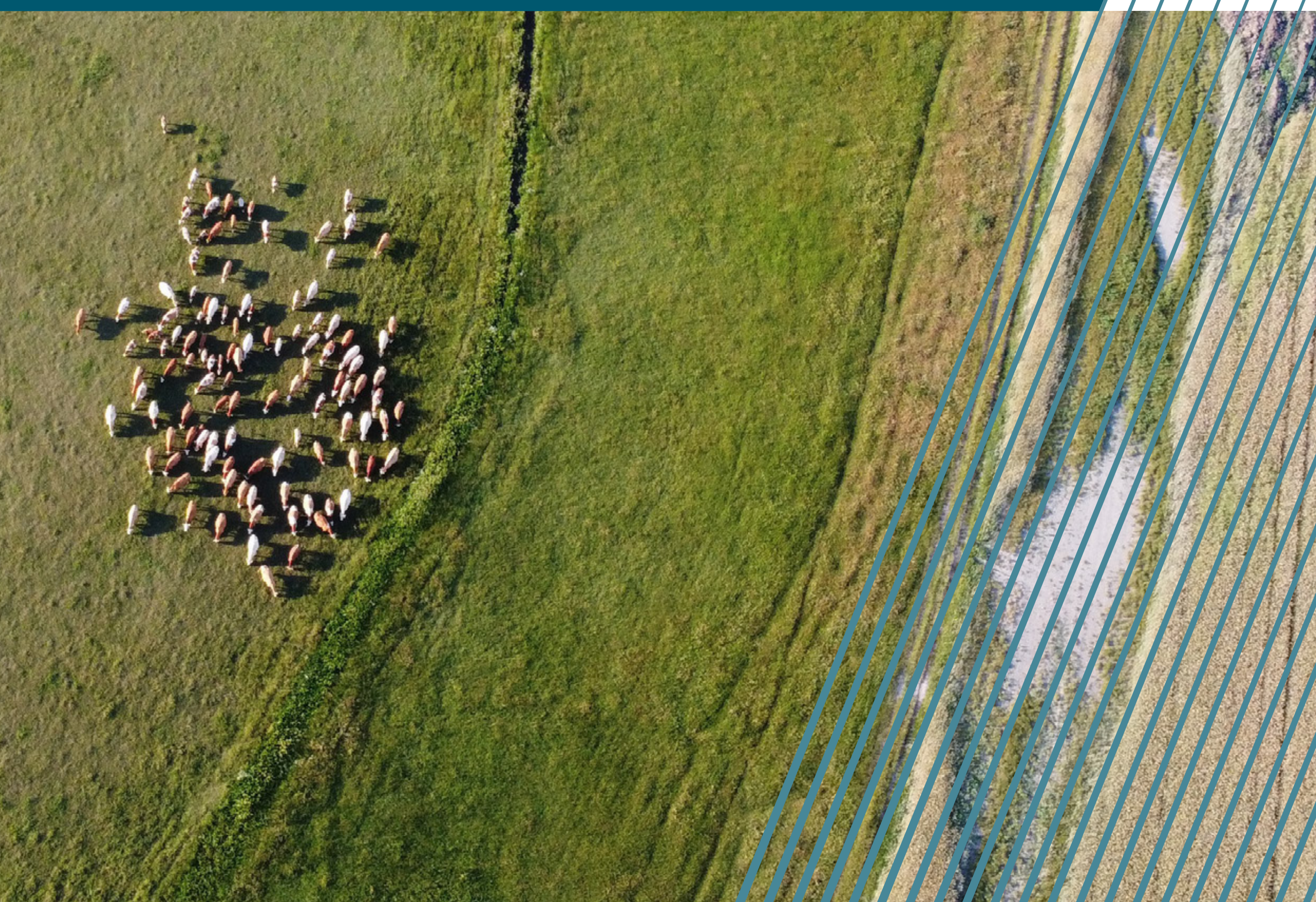

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Global assessment of soil carbon in grasslands

From current stock estimates to sequestration potential

by

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Abbreviations and acronyms

4p1000	4 per 1000 initiative
AG_{DM}	above-ground dry matter
BAU	baseline scenario
BIO	microbial biomass
C_0	estimated carbon input
C_3	plants in which the carbon dioxide is initially fixed by the Calvin cycle in photosynthesis
C_4	plants where the initial carbon fixation occurs in the outer mesophyll cells, and the Calvin cycle occurs in the inner bundle sheath cells
C_{AGR}	carbon in the above-ground residues
C_{bal}	carbon balance
C_{BGR}	carbon in the below-ground residues
C_{Exc}	carbon input from animal excreta
C_{Res}	carbon input from plant residues
DM	dry matter
DPM	decomposable plant material
FAO	Food and Agriculture Organization of the United Nations
GAEZ	Global Agro-Ecological Zones
GAUL	Global Administrative Unit Layers
GHG	greenhouse gas
GIS	geographic Information System
GLC_SHARE	Global Land Cover SHARE
GLEAM	Global Livestock Environmental Assessment Model
GPP	gross primary production
GSOCseq	global soil organic carbon sequestration
GSP	Global Soil Partnership
HUM	humidified organic matter
HWSD	Harmonized World Soil Database
IIASA	International Institute for Applied Systems Analysis
INRAE	National Research Institute for Agriculture, Food and the Environment
INT	intervention scenario
IOM	inert organic matter
IPCC	Intergovernmental Panel on Climate Change
KJWA	Koronivia Joint Work on Agriculture
LC	land cover
LCA	life-cycle assessment
LEAP	Livestock Environmental Assessment and Performance Partnership
NDC	nationally determined contribution

NPP	net primary production
RothC	Rothamsted carbon model
RPM	resistant plant material
SDGs	sustainable development goals
SOC	soil organic carbon
SOC_0	initial soil organic carbon stock
SOC_{BAU}	soil oganic carbon under the baseline scenario
SOC_{INT}	soil organic carbon under the intervention scenario
TAG	technical advisory group
UN	United Nations

CHEMICAL ELEMENTS AND FORMULAE

C	carbon
CO_2	carbon dioxide
N	nitrogen

UNITS

°C	degree Celsius
Gt	gigatonne, metric unit equivalent to 1 billion (10^9) tonnes
Pg	petagram, mass unit equivalent to 10^{15} grams.
t	time expressed in years
Mt	megatonne, metric unit equivalent to 1 million (10^6) tonnes

Context

The adoption of the Paris Agreement in 2015 paved the way for countries to commit to the international response to climate change through the transition to a low-emission economy and the development of a climate-resilient future. In livestock systems, and indeed in the whole agricultural sector, there is a need to balance the benefits of animal-source foods and livestock keeping for nutrition, health and well-being, with the urgent need to reduce greenhouse gas (GHG) emissions to tackle the climate crisis, which also threatens food security.

Grasslands contain approximately 20 percent of the world's soil organic carbon (SOC) stocks, which implies that they play a significant role in the global carbon and water cycles (Puche *et al.*, 2019). Soils can act as both sources and sinks of carbon and many grasslands have suffered losses of SOC because of anthropogenic activities such as intensive livestock grazing, agricultural uses and other land-use activities. This trend, however, could be reversed by stimulating plant growth, capturing carbon in the soil, and protecting carbon in highly organic soils.

Given the important economic, nutritional and environmental roles that grassland systems play globally, the Livestock Environmental Assessment and Performance Partnership (FAO LEAP Partnership) funded this study to illustrate the state of soil carbon stocks in grassland systems and their potential to sequester carbon in the soil.

The aim of this report is to estimate the baseline SOC stocks of grasslands in the year 2010, assess the carbon input levels needed to maintain current SOC stocks, and determine if such carbon input is available under current conditions. For these purposes, we defined improved grasslands as managed systems, and unimproved grasslands as systems close to semi-natural environments. Furthermore, this report aims to estimate the SOC sequestration potential of grasslands if management practices known to improve SOC sequestration are implemented worldwide.

Findings

SOIL CARBON STOCKS IN GRASSLANDS

The present study provides a spatially explicit report on the state of grassland soils and can be used as a baseline for future work to explore the impacts of livestock management on soil carbon at country and farm levels. Globally, there was an estimated annual uptake of 63.5 megatonne (Mt) of carbon (C) in the year 2010 in grassland soils to a depth of 30 cm, with unimproved systems storing slightly higher amounts than improved systems (33.8 vs 29.8 Mt C). On average, in the year 2010 the SOC stock under unimproved grasslands was 53 tonnes C/ha and 50 tonnes C/ha in improved grasslands. The greatest SOC stocks were found in temperate regions characterized by low decomposition rates and high grassland productivity. In comparison, the lowest SOC stocks were observed in arid to semiarid grassland soils characterized by low biomass production and organic matter decomposition, thus reducing carbon inputs into the soil. Climatic conditions explained much of the variability of SOC stock in grassland soils to 30 cm depth, followed by the carbon input to the soil from plant and animal sources, and clay content.

All together these results highlight the importance of the interaction between climate and grassland management, with the latter playing a crucial role in the quality and quantity of organic material entering the soil. Indeed, stabilization of SOC also depends on several soil properties such as soil pH, which contributes to regulating soil nutrient availability and soil particles, which protect soil organic matter by stabilizing them against microbial mineralization.

The lack of incentives for farmers to improve management practices, and the difficulty of accurately monitoring SOC stocks and changes are the main reasons for not including SOC in several countries' nationally determined contributions (NDCs) and national communication reports. The results of this report could support the inclusion of SOC targets in NDCs, which will improve NDCs' comprehensiveness and transparency for tracking and comparing policy progress across NDCs.

The uncertainty regarding the input variables, and their distribution and allocation to different land uses, together with intrinsic model uncertainties, should be carefully taken into consideration when using the results arising from this work on the current state of the carbon in the soil, and its potential to be sequestered in grassland soil. The estimation of the global soil carbon stock is still quite uncertain, and improved geostatistical methods are urgently needed to reduce the propagation of such uncertainties in soil models. To improve the accuracy of input data, such as soil, animal and vegetation properties, and C exchange information, it is crucial to generate local datasets, especially from underrepresented regions (e.g. Africa), and explore differences among existing datasets.

ASSESSMENT OF CURRENT CARBON STOCK LEVELS

The majority of grassland soils seem to receive enough organic material to maintain current carbon stock levels. Improved grasslands needed, on average, higher carbon inputs than unimproved systems to sustain current SOC stocks (2.1 vs 1.3 tonnes C/ha/year). Moreover, the positive soil carbon balance found in both improved and unimproved systems globally indicates a potential increase in SOC stocks. Despite such a positive trend globally, the large spatial variability of these estimates highlights that the soil state at country level could differ greatly from the global estimates. The majority of grasslands have a positive carbon balance meaning that the land is stable or even under improved biophysical conditions. However, negative carbon balance was found in East Asia, Central and South America, and Africa south of the Equator, meaning that current SOC stocks are likely to be decreasing due to anthropogenic stresses combined with climatic conditions. No specific global measurements are currently available, and it is worth mentioning that the diversity of situations – in terms of climate, soils and management practices – might have been crucial for soil carbon dynamics in these areas, as represented by the variability of the carbon input values in grassland systems.

The findings of this analysis show that there is room for additional carbon storage in some grassland soils. The main recommendations for grassland systems are to prioritize carbon returns in deteriorated soils that have a negative carbon balance, and to protect SOC in areas – particularly under unimproved grasslands – with high carbon stocks. Grasslands could contribute to the recarbonization of degraded land and the results of the present study can highlight hotspots where interventions on grasslands are needed to preserve or increase SOC in the long term.

SOIL CARBON SEQUESTRATION POTENTIAL

This study found that if the SOC content in the 0–30 cm depth layer of available grasslands increased by 0.3 percent after 20 years of the application of management practices that enhance SOC sequestration, 0.3 tonnes C/ha/year could be sequestered. Sub-Saharan Africa and South Asia show the highest potential for carbon storage on a per hectare basis (0.41 and 0.33 tonnes C/ha/year, respectively), followed by Oceania, North America and East Asia. Low levels of SOC on grasslands, much of it with serious degradation issues, provide the opportunity to enhance SOC sequestration.

The 4p1000 initiative has identified an aspirational sequestration target of 3.5 Pg C/year to provide substantive global mitigation. Our estimates suggest that 17 percent of this target could be reached in the top 30 cm of grasslands and continue over at least 20 years after adoption of SOC enhancing management, such as the incorporation of animal manures, agroforestry and rotational grazing. This requires that grasslands increase SOC storage between 0.18–0.41 tonnes C/ha every year. Our estimates do not account for differences in climate and important soil process issues, notably nutrient and water limitations, biomass production and turnover rates. However, sequestering carbon via increases in the soil component on grasslands is an achievable and potentially effective route to quickly increasing carbon sequestration in the near term. Emphasis on future work should be placed on spatially explicit studies to explore the impacts of livestock management practices at country level and to monitor management-induced carbon sequestration in livestock-based ecosystems at farm level.

Despite the large technical potential to sequester carbon in soils, there are often significant limitations to achieving that potential in any particular place and within specific farming systems. In addition, there may be trade-offs with productivity, food security or hydrologic balances, as well as concerns regarding other GHGs, such as N_2O. Therefore, for a full system budget, it is imperative to include estimates of changes in methane emissions in order to understand the environmental impacts of management practices on the full grassland system. Future work should be focused on including soil carbon estimates in life cycle analyses. The main challenges would be to develop a methodology to allocate SOC stocks to different livestock units and to account for temporal and spatial dynamics of carbon in the soil. Nevertheless, this would enable accurate life cycle assessment of livestock systems as well as the development of targeted livestock sector-driven national policies for climate change mitigation and adaptation, and food security.

1. Introduction

The adoption of the Paris Agreement in 2015 paved the way for countries to commit to the international response to climate change through the transition to a low-emission economy and the development of a climate-resilient future. Since the global annual carbon dioxide (CO_2) emissions from fossil fuels and all other sources are ~10 Gt of carbon (Boden, Marland and Andres, 2017), soil organic carbon (SOC) has been proposed as a plausible partial climate mitigation strategy which can offset part of the greenhouse gas emissions (GHG) derived from anthropogenic activity, with an estimated global sequestration potential of 30–60 Gt of carbon (Lal, 2004; Sommer and Bossio, 2014), and might buy time while low-carbon technologies are being developed and adopted. In livestock systems, there is a need to balance the benefits of animal-source foods and livestock keeping for nutrition, health and well-being, with the urgent need to reduce GHG emissions to tackle the climate crisis, which also threatens food security.

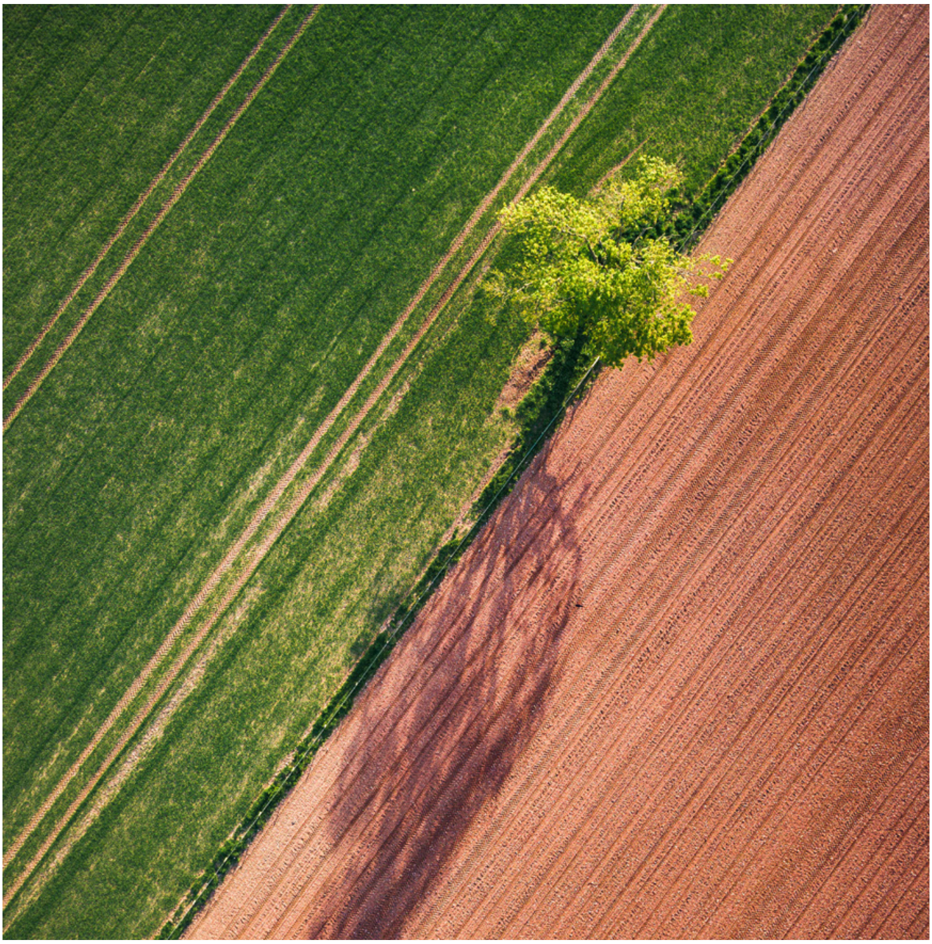
In 2017, the 23rd Conference of Parties adopted the Koronivia Joint Work on Agriculture (KJWA) to discuss the role of agriculture in climate action while considering the vulnerability of the sector to climate change and addressing food security. The KJWA plays a crucial role in enabling the livestock sector to contribute to climate action by mobilizing knowledge, technology, finance and capacity. It acknowledges the strategic importance of livestock including key areas such as improved soil carbon sequestration in grazed grasslands, improved nutrient use and manure management and improved livestock management systems (Uwizeye *et al.*, 2021). It is therefore evident that assessing the current state of grassland systems, and their potential to sequester carbon in the soil, is of key importance for understanding the trade-offs between grassland services on food security, biodiversity conservation and climate mitigation, and how current grassland management could be improved to meet climate targets.

Grasslands are ecological communities dominated by grasses with little to no tree or shrub cover. Some grasslands are natural, while other grasslands have been created from other forms of vegetation, notably forest. Humans use grasslands for grazing, but not all grasslands are grazed by domesticated animals. Some may be protected (i.e. grazing is prohibited) and others are located in regions that simply cannot support them (Garnett *et al.*, 2017).

Grasslands are among the largest ecosystems in the world, occupying 3.5 billion ha (FAOSTAT, 2016), of which almost 2 billion ha are used for grazing livestock (FAOSTAT, 2016; Mottet *et al.*, 2017).

Natural grasslands (often called rangelands) are dominated by perennial grasses whose species composition has not been altered to improve livestock productivity.

Improved grasslands (often called pastures) are more intensively maintained, and highly productive. These grasslands have been modified by sowing more nutrient-rich grasses or legumes, and by using fertilizers, other amendments and sometimes irrigation to support more intensive livestock grazing. Improved pastures are species poor. Sometimes the grass



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is mowed to produce silage for winter feed. The animals themselves may receive feed supplements, in which case the dung they deposit loads the soil with externally produced nutrients (Garnett *et al.*, 2017).

Semi-natural grasslands can be broadly defined as 'habitats created by low-intensity, traditional farming, or, in some cases, the natural vegetation on poor soils or in exposed locations' (Garnett *et al.*, 2017). The semi-natural grassland is a very fluid habitat, which is amenable for conversion to (and from) arable land and to improved grassland through cultivation, re-sowing and fertilizer application (Garnett *et al.*, 2017). While they tend to provoke a great deal of definitional debate, 'semi-natural' grasslands have been defined here to distinguish them from more intensively managed pastures and from 'natural' grasslands.

Soils store significant amounts of carbon as soil organic matter, globally about 2.3 times more than the carbon in atmospheric CO_2 and 3.5 times more than the carbon in all living terrestrial plants (Yang *et al.*, 2019). Global grasslands are important components of the terrestrial carbon cycle, storing 119–121 Gt C (Erb *et al.*, 2018) in vegetation biomass, about 343 Gt C in the top one meter of soil (Conant *et al.*, 2017) and a potential soil sequestration rate of 0.5 tonnes C/ha per year (Henderson *et al.*, 2015; Conant *et al.*, 2017).

The SOC stock in grasslands is determined by the balance between carbon inputs and outputs. Carbon inputs are derived naturally from the annual photosynthetic carbon uptake of all leaves in a grassland in the form of root exudates and litter (i.e. gross primary production (GPP)). The net primary production (NPP) of grasslands is the net carbon stored as new plant material before harvest and other losses. Additional carbon inputs are derived from animal manure. Carbon losses occur through natural processes of respiration, decomposition, erosion, leaching, fire and removal of biomass by grazing animals, and by human interventions through biomass harvesting. Management interventions, such as mowing versus pasture and grazing intensity (i.e. the fraction of NPP consumed by grazing animals), may particularly influence the SOC stocks. When grasslands are grazed, biomass ingested by animals contains digestible and non-digestible organic compounds. The non-digestible carbon fraction (25–40 percent) of the intake is returned to the soil through excreta (i.e. dung and urine). The digestible part is respired as CO_2 shortly after intake (Chang *et al.*, 2015). Only a small fraction serves to increase animal mass (e.g. muscles) or to form animal products (e.g. milk) which are exported from the grassland ecosystem (Soussana, Tallec and Blanfort, 2010). Another small part of the digested carbon is emitted in the form of methane by ruminant enteric fermentation and manure management systems (Sejian *et al.*, 2012).

The soils of managed grasslands contain ~20 percent of the world's SOC stocks, which implies that they play a significant role in the global carbon and water cycles (Puche *et al.*, 2019). Soils can act as both sources and sinks of carbon and many grasslands have suffered losses of SOC because of anthropogenic activities such as intensive livestock grazing, agricultural uses and other land-use activities. This trend, however, could be reversed by practices aimed at stimulating root and plant growth (e.g. grazing and nutrient cycling) and by helping carbon move from above ground to below ground, where it can be captured. These practices can also stabilize productivity and generate significant social, economic and environmental benefits.

Current literature suggests no clear relationships between grazing management and carbon sequestration (Conant *et al.*, 2017). However, positive carbon sequestration was reported for light-to-moderate grazing intensities (Abdalla *et al.*, 2018), while overgrazing was found to have a negative effect on SOC stocks (Dlamini, Chivenge and Chaplot, 2016). The interactions of carbon and nitrogen in soils are of great importance for regulating the main ecological processes such as nutrient cycling and energy flow (Sardans, Rivas-Ubach and Peñuelas, 2012). Sufficient nitrogen needs to be available for plants to grow, and therefore for soils to sequester carbon. This can be provided in the form of bacterial nitrogen fixation or the application of mineral fertilizers or organic amendments containing nitrogen (Liu *et al.*, 2020). These nitrogen inputs to the soil can promote carbon sequestration but would also cause methane and nitrous oxide to be emitted. Hence, the net GHG balance will depend upon whether the sequestration gains outweigh these other emissions.

Generally, best management techniques yielding increases in SOC stocks rely on the management of grazing intensities, as well as increasing forage production through improved species. The sequestration of soil carbon arising from grassland management could, therefore, be significant (Lorenz and Lal, 2018) and this, in turn, could have a positive effect on soil health and other ecosystem services. One critical co-benefit of building carbon in soil is improved nutrient availability and cycling, which can improve soil fertility while reducing the need for chemical fertilizers. Numerous soil functions and ecosystem services depend on SOC and its dynamics. Improvements in soil health, along with an increase in the availability of water and nutrients, increase soil's resilience against extreme climate events (e.g. drought, heat wave) and impart disease-suppressing attributes, which in turn can also improve animal health. Enhancing and sustaining soil health is also pertinent to achieving the goals of the United Nations Decade on Ecosystem Restoration and advancing the Sustainable Development Goals (SDGs) outlined in the United Nations 2030 Agenda for Sustainable Development (e.g. alleviating poverty, reducing hunger, improving health, climate action, life on land, and promoting economic development).

This study is part of the deliverables of the Livestock Environmental Assessment and Performance Partnership (FAO LEAP Partnership). The FAO LEAP Partnership is a multi-stakeholder initiative that is committed to improving the environmental performance of livestock supply chains, whilst ensuring their economic and social viability. It is composed of three stakeholder groups: governments, private sectors, and civil society and non-governmental organizations (NGOs). FAO LEAP Partnership develops comprehensive guidance and methodology for understanding the environmental performance of livestock supply chains, and to shape evidence-based policy measures and business strategies. Technical advisory groups (TAGs) – groups of experts from academia, private sectors and NGOs – are formed to develop the guidance and methodology for measuring environmental performance. The soil carbon TAG conducted the background research and developed the core technical content of the guidelines for measuring and modelling soil carbon stocks and stock changes in livestock production systems (FAO, 2019). The aim of these guidelines is a harmonized, international approach for estimating SOC stock and stock changes in livestock production systems. A set of methods and approaches is recommended for use by individual farmers or land managers, those undertaking life cycle assessment of livestock products, policy makers, and regulators at local, regional or national scales.

Given the important economic, nutritional and environmental roles that grassland systems play globally, the FAO LEAP Partnership funded this study to illustrate the state of soil carbon stocks in grassland systems and their potential to sequester carbon in the soil.

The specific objectives of this work were:

- To assess the baseline SOC stocks of grasslands in the year 2010;
- To assess the organic carbon input levels needed to maintain current SOC stocks, and determine if such carbon input is available under current conditions; and
- To obtain a first estimate of SOC sequestration potential of grasslands, if management practices known to improve SOC sequestration are implemented worldwide.

2. Methods

2.1 FAO LEAP GUIDELINES

LEAP guidelines for SOC assessment describe the approaches to model SOC stocks and changes in livestock production systems. Three modelling approaches have been recommended in the LEAP guidelines, namely: empirical models (Level 1), soil models (Level 2) and ecosystem models (Level 3).

Empirical models estimate SOC stocks and changes using an empirical approach, which usually represents the observed relationships between SOC stocks or SOC changes and defined variables (environmental and/or management), such as soil texture, climate, land use or management practices (Grigal and Berguson, 1998; Davidson and Janssens, 2006). The LEAP guidelines for SOC assessment recommend using these models to provide a first estimate of the expected SOC change direction or amplitude.

Soil models estimate SOC stocks and changes by simulating SOC dynamics through time, considering the effects of climatic and soil factors together with land use and management variables. Models at this level are process-oriented; they are generally used to predict SOC dynamics based on different conceptual carbon pools or compartments that vary in size via inputs, decomposition rates and stabilization mechanisms. Soil models focus on the processes mediating the movement and transformations of soil carbon only. Each soil organic matter pool within a model is characterized by its position in the model structure and its decay rate. Decay rates are usually expressed by first-order rate kinetics (Paustian *et al.*, 1997) for the concentration of the pool over time. To include estimates of changes in SOC stocks in life-cycle assessments (LCA), the LEAP guidelines for SOC assessment recommend using at least a Level 2 model to estimate SOC after a land management change.

Ecosystem models are process-oriented and consider the effects of climate, soil, land use and management variables on SOC dynamics. However, these models simulate soil processes other than carbon turnover that may have a direct or indirect impact on SOC dynamics. Thus, Ecosystem models are built by different sub-models simulating above- and below-ground plant biomass, soil water dynamics, nutrient dynamics, and their interactions.

The purpose of the present study was to focus on soil carbon only, therefore Ecosystem models were not included, while both Empirical and Soil models were integrated into the methodology.

2.2 FRAMEWORK AND METHODOLOGY DEVELOPMENT

The LEAP recommendations set the benchmark for the development of a framework for assessing SOC stocks and potential SOC sequestration in grassland systems at global level.

The Tier 2 approach (Level 2 – soil model) recommended in the LEAP guidelines for SOC assessment was used to estimate the baseline SOC stocks in grassland systems, providing global reference conditions of grassland soils for the year 2010.

Among the Soil models suggested in the LEAP guidelines, the Rothamsted Carbon model (i.e. RothC; Coleman and Jenkinson, 1996) was selected, as it is one of the most commonly used soil process-based models. RothC simulates the turnover of organic carbon in non-waterlogged topsoil using a monthly time step to estimate total SOC. The model has been widely tested and used at the plot, field, regional and global scales, using data from long-term field experiments from different locations (Diels *et al.*, 2004; Pramod *et al.*, 2021).

RothC uses a pool-type approach, describing SOC as pools of inert organic matter (IOM), humus (HUM), microbial biomass (BIO), resistant plant material (RPM) and decomposable plant material (DPM). During the decomposition process, material is exchanged between the SOC pools according to first-order rate equations. These equations are characterized by a specific rate constant for each pool. These rates are adjusted according to rate modifiers which are dependent on the temperature, moisture, and crop cover of the soil. The decomposition process results in gaseous losses of carbon dioxide (CO_2). The type of vegetation influences the distribution of carbon inputs into the RPM and DPM pools, hence the DPM:RPM ratio typically depends on the vegetation type. In RothC, four vegetation types are considered: croplands, improved grasslands, unimproved grasslands, and forests with a DPM:RPM ratio of 1.44, 1.44, 0.67 and 0.25 respectively. For a given total carbon input and mineralization rate, land use with lower values of the DPM:RPM ratio will exhibit higher total SOC stocks.

The Tier 1 approach (Level 1 – empirical model) recommended in the LEAP guidelines for SOC assessment was selected to explore the global potential of grassland systems to sequester carbon. This analysis illustrates where and how much carbon might be sequestered if – through improved practices and management – SOC on grasslands can be increased by a generally accepted (as attainable) moderate amount, based on the medium sequestration scenario of Sommer and Bossio (2014) and Zomer *et al.* (2017). This empirical approach has been chosen over a process-based methodology to reduce uncertainties on management data. As countries, and even farms, adopt different practices based on ecological and socio-economic constraints, it can be difficult to determine a spatially explicit distribution of management practices tailored to increase soil carbon. Instead, an empirical approach was adopted to estimate the percent increase of SOC attainable under improved management, such as the incorporation of animal manures, agroforestry, rotational grazing, or other practices that are known to increase soil carbon at the decadal scale. This approach provides a general framework for countries with limitations on their ability to implement more complex, intensive data requiring, process-oriented modelling approaches.

The two approaches presented here require specific input data and distinct modelling assumptions. Full details on data requirements and model initialization of both approaches are given in the following sections. Due to the nature of the methodology used, the estimated baseline SOC stocks for the year 2010 and the soil carbon sequestration potential of grassland systems will be analyzed and discussed independently.

2.3 ASSESSING THE BASELINE SOIL CARBON STOCKS OF GRASSLAND SYSTEMS

The estimation of changes in SOC by the Tier 2 Soil model, due to either land-use or management changes, requires model initialization. Initialization refers to setting the initial SOC condition (total SOC and SOC of the different pools) at the start of the period over which stocks will be estimated, so that further simulated results are realistic estimates.

The Harmonized World Soil Database (HWSD) version 1.2 was used to provide initial soil conditions in the model (FAO, IIASA, ISRIC, ISS-CAS & JRC, 2012). The HWSD is a 30 arc-second raster database with over 15 000 different soil mapping units that combines existing regional and national updates of soil information worldwide with the information contained within the 1:5 000 000 scale FAO-UNESCO Soil Map of the World. The HWSD provides soil data to a depth of 1 meter at a resolution of 30 arc s (approximately 1 km), for the dominant soil types in each grid cell. The soil properties used from this database to drive the RothC model for the top 30 cm soil depth were: organic carbon content, bulk density, coarse fragments and clay fraction. The RothC model is run for the dominant soil type (percentage of grid cell area > 50 percent) in each grid cell at a soil depth of 30 cm.

RothC requires monthly precipitation and air temperature data which are used to determine temperature-based rate modifiers for various soil processes. The annual monthly statistics on averaged mean temperature and sum of precipitation were derived from the AgMERRA climate dataset (i.e. 0.5 deg spatial resolution) (Ruane, Goldberg and Chryssanthacopoulos, 2015) for years from 1980 to 2010.

Land cover was estimated using the Climate Change Initiative (CCI) Land Cover (LC) data v2.0.7 (ESA, 2017) for the year 2010. The CCI-LC predictions (300 meters spatial

TABLE 1
CCI-LC classes reclassified into improved and unimproved grasslands

CCI-LC class	New class used in this study
Mosaic cropland (>50%) / natural vegetation (tree, shrub, herbaceous cover) (<50%)	Improved
Mosaic natural vegetation (tree, shrub, herbaceous cover) (>50%) / cropland (<50%)	Improved
Grassland	Improved
Mosaic tree and shrub (>50%) / herbaceous cover (<50%)	Unimproved
Mosaic herbaceous cover (>50%) / tree and shrub (<50%)	Unimproved
Shrubland	Unimproved
Sparse vegetation (tree, shrub, herbaceous cover) (<15%)	Unimproved

resolution) were grouped into two main categories reflecting the grassland categories given in the RothC model, namely improved and unimproved grasslands. We reclassified CCI-LC classes into improved and unimproved grasslands on the RothC assumption that improved systems are managed systems, while unimproved grasslands are close to semi-natural environments (Table 1). A full description of the CCI-LC classes and their direct link with the Land Cover Classification System developed by the United Nations can be found in the CCI-LC product user guide (ESA, 2017).

Simulations were only performed on these two categories and their distribution is shown in Map 1. For improved grassland, we used a DPM:RPM ratio of 1.44 (i.e. 59 percent of the plant material is DPM and 41 percent is RPM). For unimproved grassland, a ratio of 0.67 was used.

The annual plant residue input was estimated following the Intergovernmental Panel on Climate Change (IPCC) methodology (IPCC, 2006). The carbon input from plant residues (C_{Res}) was calculated using the sum of above-ground and below-ground residues, which were then converted into their carbon content.

$$C_{Res} = C_{AGR} + C_{BGR} \qquad \textbf{Eq.1}$$

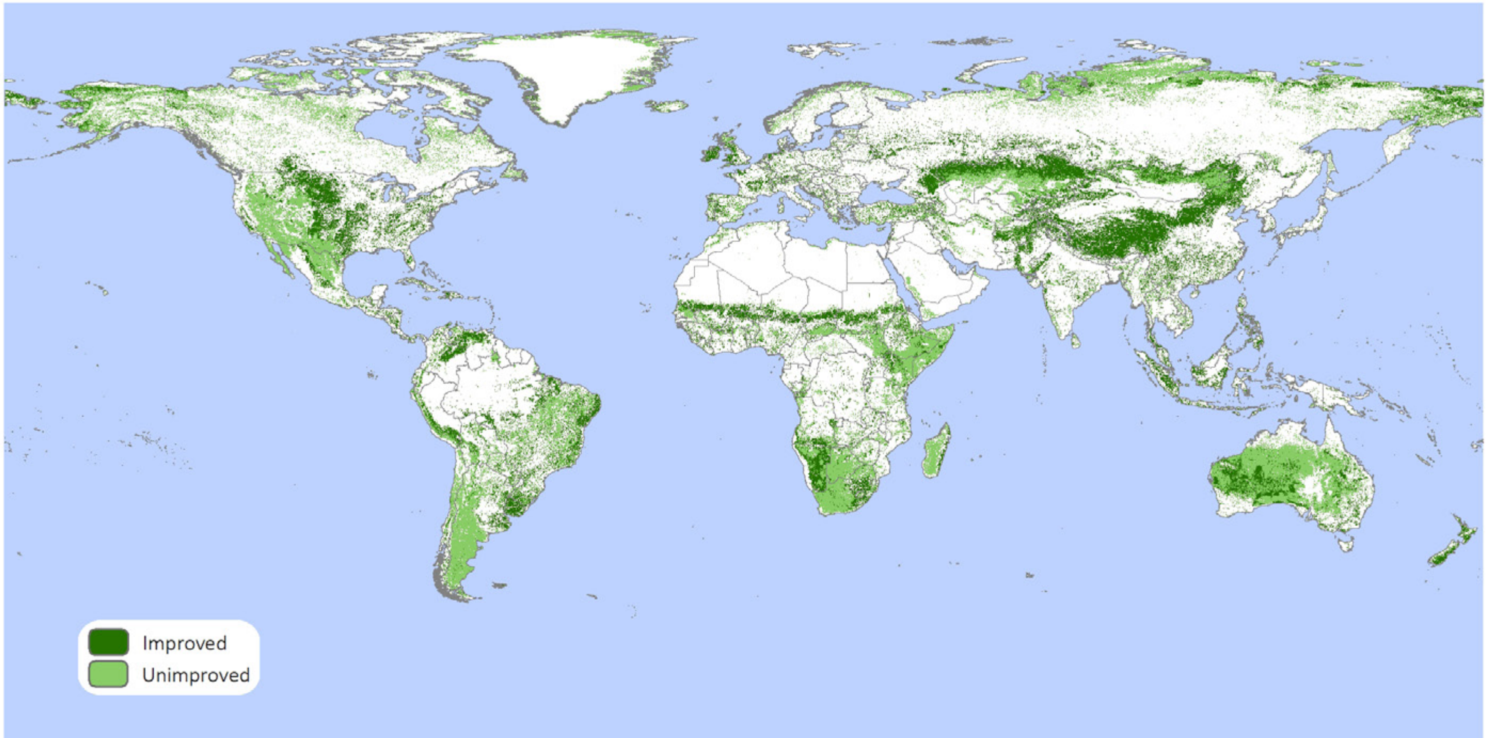
Where C_{AGR} is the carbon in the above-ground residues and C_{BGR} is the carbon in the below-ground residues.

Following Chapter 11 of the IPCC methodology (IPCC, 2019), the above-ground residues can be estimated as a function of the total yield and then converted into carbon content as follows:

$$C_{AGR} = (AG_{DM} \times 0.3) \times 0.475 \qquad \textbf{Eq. 2}$$

Where AG_{DM} is the above-ground dry matter.

MAP 1
Spatial distribution of unimproved and improved grassaland systems



Source: **United Nations Geospatial.** 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from ESA, 2017.

The same approach can be used to estimate the carbon content from the below-ground biomass residues:

$$C_{BGR} = (BG_{DM} \times 0.9)$$ **Eq. 3**

Where BG_{DM} is the below-ground dry matter.

Data on above-ground dry matter per hectare for the year 2010 were estimated by the GLEAM 2.0 model (FAO, 2020a). Data on fresh matter yields per hectare, and their respective land area, were taken from a modified version of Global Agro-Ecological Zones (GAEZ 3.0) (IIASA and FAO, 2012) and Haberl *et al.* (2007) to estimate the above-ground net primary productivity for grassland. To this scope, the fresh matter was converted into dry matter content, with dry matter being 90 percent of fresh (Opio *et al.*, 2013).

Carbon input from animal excreta (C_{Exc}) was estimated from the nitrogen deposited in 2010, which was calculated by the GLEAM 2.0 model. The function of the GLEAM 'Manure' module is to calculate the losses of nitrogen through manure management systems and the rate at which excreted nitrogen is applied and deposited (FAO, 2020a). The deposited nitrogen is then converted into carbon by applying a mean C:N ratio of 17.5 (FAO, 2015a), and then used as input in the RothC model.

All above input variables were harmonized to a 1 km spatial resolution and the RothC model was first initialized using a long 'spin-up' simulation (i.e. 10 000 years) (Coleman and Jenkinson, 1996), to estimate the soil pool ratios by iteratively adjusting the carbon inputs such that the SOC from the HWSD dataset was reproduced. Then a short 'warm-up' simulation of 30 years was used to estimate the soil conditions for the year 2010 (FAO, 2019; FAO, 2020a). The year 2010 was chosen for consistency with the data derived from the GLEAM 2.0 model and to align the potential SOC estimated by the RothC model with the GHG emissions estimated by the GLEAM 2.0 model.

The Global Administrative Unit Layers (GAUL) database (FAO, 2015b) was used to analyze results by region. This choice was made to align the results of this study with the LCA analysis on livestock systems performed with the GLEAM model.

The Pearson correlation test was used to investigate the dependence between multiple variables used to drive the RothC model and the simulated SOC (Smith and Smith, 2007). In particular, correlation tests were performed among simulated SOC (baseline SOC), initial SOC (HWSD soil carbon data), potential evapotranspiration, air temperature, precipitation, and organic carbon inputs to the soil.

The sensitivity of RothC to different input parameters was investigated to quantify the effects of such parameters on the simulated SOC (Smith and Smith, 2007). Only one parameter was changed at a time, while the others were kept constant. Simulations were run to assess how SOC was affected by changes in average temperature (increased/decreased by a range from -2 degree Celsius (°C) to +2 °C with an increment of 1 °C), initial SOC content (decreased/increased by a range from -50 percent to +50 percent with an increment of 20 percent or 30 percent), and total carbon inputs (decreased/increased by a range from -50 percent to +50 percent with an increment of 20 percent or 30 percent). For each scenario, the relative change in SOC was calculated as a percentage. All analysis was performed using R software version 4.0.3 (R Core Team, 2013).

2.4 ASSESSING CARBON INPUT LEVELS NEEDED TO MAINTAIN CURRENT SOIL ORGANIC CARBON STOCKS

The RothC model is designed to run in two modes: "forward" in which known carbon inputs are used to calculate the changes in soil organic matter, and "inverse" when carbon inputs are calculated at an equilibrium state for 10 000 years from known changes in soil organic matter. In this study, the model was run at equilibrium in inverse mode to predict the plant input required to maintain current SOC levels. Prior to initializing the model in inverse mode, the equation developed by Falloon *et al.* (1998) was used to estimate the size of the IOM pool from the known SOC stock. The remaining SOC stock (i.e. the total stock minus IOM) is then used as the input variable, and carbon inputs into the soil are iteratively adjusted until this input value is reached.

$$IOM = 0.049 \times SOC^{1.139}$$ **Eq. 4**

When run in inverse mode, RothC needs only two input data related to management. The first one is the number of months when soils are left bare. This input variable was set to zero months for all grasslands, as grassland ecosystems are never left bare. The second input variable is the proportion of carbon inputs to the soil that consists of organic amendments. The organic carbon inputs to the soil are mainly the result of plant residues and additions of animal manure and other organic products. In RothC, the fate of carbon provided by plant residues and organic amendments is specific, reflecting their difference in terms of decomposability. Therefore, to use RothC for estimating the amount of carbon input needed to maintain current levels of SOC stocks, the proportion between C_{Res} and C_{Exc} was estimated.

The estimated carbon input (C_0) was then compared against total carbon input (C_{Res} + C_{Exc}) to assess if the carbon input needed to maintain current SOC levels is available under current conditions (Martin *et al.*, 2021). The carbon balance (C_{bal}) of a given soil is therefore defined as the difference between available carbon inputs (C_{Res} + C_{Exc}) and the carbon input (C_0), as estimated with the RothC model.

$$C_{bal} = (C_{Res} + C_{Exc}) - C_0$$ **Eq. 5**

If C_{bal} differs from zero, the steady-state hypothesis is currently not valid. $C_{bal} < 0$ indicates that the current total carbon input is not sufficient to sustain existing SOC stocks, hence resulting in a SOC declining trend. If $C_{bal} > 0$, SOC stocks might be on an increasing trend.

The Global Administrative Unit Layers (GAUL) database (FAO, 2015b) was used to analyse results by region.

2.5 ASSESSING SOIL ORGANIC CARBON SEQUESTRATION POTENTIAL IN GRASSLAND SYSTEMS

The global potential of grassland systems to sequester carbon in the soil was estimated by using an empirical approach based on a methodology developed by Zomer *et al.* (2017). This approach estimates the percent increase of SOC attainable after 20 years of improved management practices. A geospatial analysis is then used to estimate the potential attainable SOC sequestration in grassland systems and to identify opportunities for SOC sequestration worldwide.

The initial SOC (tonnes C/ha), bulk density (kg/m^3) and sand content (weight percent) at 0 – 30 cm soil depth were extracted from the Soils Grid (i.e. 250 m spatial resolution - ISRIC World Soil Information) (Hengl *et al.*, 2014).

The Global Land Cover SHARE Beta-Release v1.0 (i.e. GLC_SHARE) (FAO, 2014) was used to identify grassland extent and distribution. This geospatial database provides an estimate of the percent of land-cover area within a 1 km grid cell. The GLC_SHARE dataset was resampled to allow for the analysis and geoprocessing at the finer 250 m (0.002083333 degrees) resolution of the soil data. The designation grassland is based upon the UN Land Cover Classification System, and includes any geographic area dominated by natural herbaceous plants (grasslands, prairies, steppes and savannahs) with a cover of 10 percent or more, irrespective of different human and/or animal activities, such as grazing, selective fire management, etc. Woody plants (trees and/or shrubs) can be present assuming their cover is less than 10 percent.

The geospatial analysis used to estimate the potential attainable increase of SOC on grassland after twenty years is described in detail in Sommer and Bossio (2014) and Zomer *et al.* (2017). The increase in percent-SOC in response to improved management was described in Sommer and Bossio (2014) with a four-parameter sigmoid function of the form:

$$SOC = SOC_0 + \frac{a}{1+e^{-\frac{t-t_0}{b}}} \qquad \textbf{Eq. 6}$$

where SOC_0 is the initial SOC content (percent), a and b are empirical constants, t is the time expressed in years, and t_0 is the year where the slope of the curve is largest (i.e. the highest annual sequestration rate). The parameters for the scenario based upon Sommer and Bossio (2014) were:

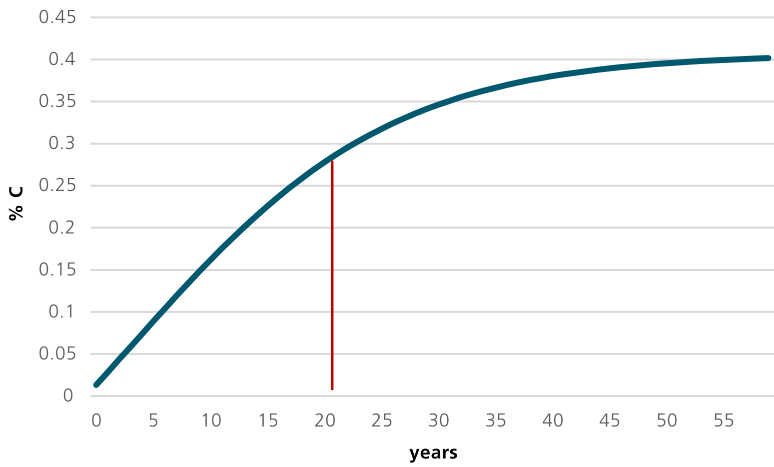
$$a = 0.697; \qquad b = 11.5; \qquad t_0 = 4$$

The percent increase of SOC after 20 years was calculated from this curve (Figure 1) and resulted in a value of 0.27.

Bulk density was used to first convert SOC (tonnes C/ha) (as presented in the Soils Grid 250 m data) into SOC (percent). The estimated percentage increase of SOC (i.e. 0.27 percent increase) was then added to SOC (percent), and the result was converted back to SOC (tonnes C/ha).

High SOC soils (i.e. soils with a weighted average bulk density (0–30 cm) equal to or less than 1.0 kg/m^3 and/or with more than 400 tonnes C/ha) were excluded from further analysis. Sandy soils (i.e. sand content at 15 cm equal to or greater than 85 percent) were also excluded from further analysis. These soils were excluded because their potential for sequestering carbon would be negligible.

FIGURE 1
Percent increase of soil organic carbon (SOC) in response to improved management



Source: **Sommer, R. & Bossio, D.** 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management*, 144: 83–87. https://doi.org/10.1016/j.jenvman.2014.05.017

All result grids were converted into World Sinusoidal projection to allow for area calculations. The GLC_SHARE – Dominant (Class 3 = Grassland) dataset (FAO, 2014), in percent area of a 1 km grid cell, was resampled to 250 m and multiplied times the various results (tonnes C/ha) to calculate actual total tonnes of carbon in each grid cell (i.e. given the actual area of grassland in that grid cell). The Global Administrative Unit Layers (GAUL) database (FAO, 2015b) was used to analyse results by region.

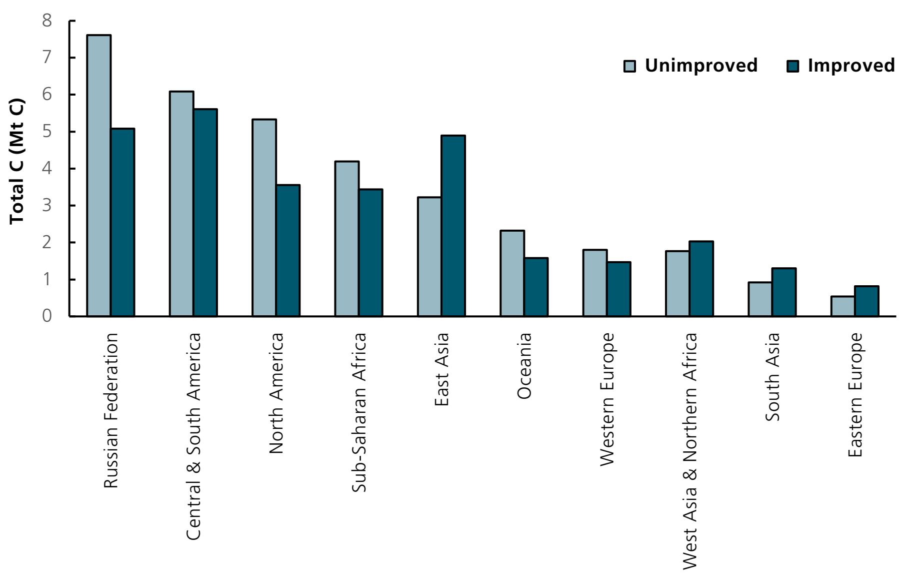
3. Results

3.1 GLOBAL BASELINE SOIL ORGANIC CARBON STOCKS

Globally, grassland soils stored an estimated 63.5 Mt of carbon in the year 2010 at 30 cm soil depth, with unimproved systems storing slightly higher amounts than improved systems (33.8 vs 29.8 Mt C). In unimproved grassland systems, the Russian Federation and the Americas stored the highest amount of SOC among all regions, while South Asia and Eastern Europe stored less than 1 Mt C each. In improved grasslands, Central and South America was the region with the highest SOC socks (5.6 Mt C), followed by the Russian Federation (5.1 Mt C) and East Asia (4.9 Mt C). Eastern Europe was the only region with SOC stocks values below 1 Mt C, while the other regions ranged from 1.3 Mt C in South Asia to 3.5 Mt C in North America (Figure 2).

On average, in the year 2010 the SOC under unimproved grasslands was 53 tonnes C/ha and 50 tonnes C/ha in improved grasslands. Global distribution of SOC is strongly influenced

FIGURE 2
Regional total (cumulative) soil organic carbon (SOC) estimated for the year 2010 by the RothC model for improved and unimproved grassland worldwide



Source: **UN**. 2020. *Map of the World*, modified with data from **Coleman, K. & Jenkinson, D.S.** 1996. RothC-26.3 - A Model for the turnover of carbon in soil. In: Powlson, D.S., Smith, P., Smith, J.U., eds. *Evaluation of Soil Organic Matter Models*. NATO ASI Series, 38: 237-246. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-61094-3_17

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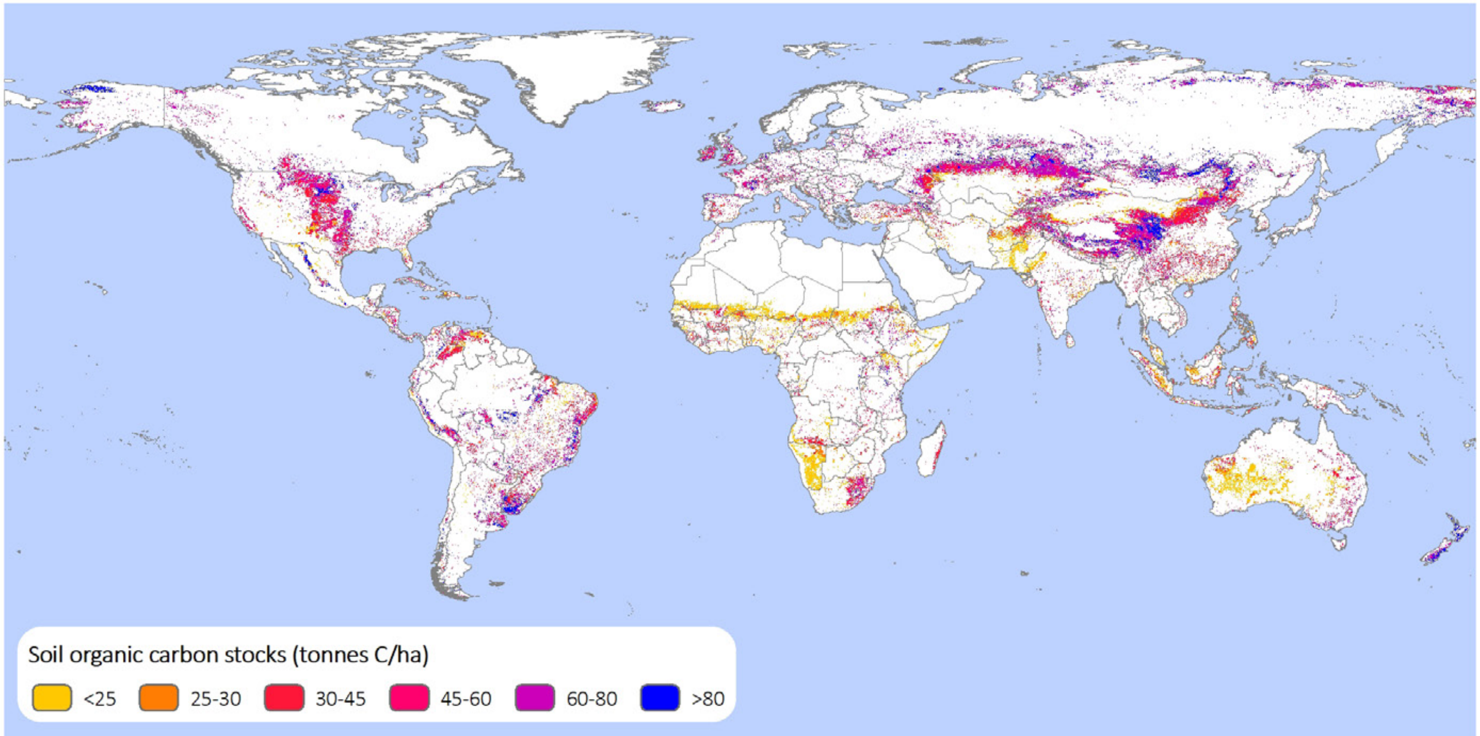
by temperature and precipitation. SOC is generally lower in the tropics where it is hotter and/or drier, and higher in the cooler and wetter latitudes. The spatial distribution of SOC in improved (Map 2) and unimproved grasslands (Map 3), and its contribution to total carbon stock differs substantially from the northern to the southern hemispheres. Most of the world's SOC is stored at northern latitudes, particularly in the permafrost and moist boreal regions. In contrast, large areas of grassland in East Asia, across sub-Saharan Africa and some areas in North America are found on low carbon density soils.

The regions of the Russian Federation, Europe and North America store the greatest amount of soil carbon on a per hectare basis in improved systems, with 76 tonnes C/ha, 61 tonnes C/ha and 60 tonnes C/ha, respectively (Map 2). In unimproved systems, these same regions store higher amounts of carbon in the soil, with values ranging from 92 tonnes C/ha in the Russian Federation to 56 tonnes C/ha in North America (Map 3). The Russian Federation region accounts for more than 50 percent of all SOC stocks globally. Together with North America, these two regions appear to have not suffered human-induced soil degradation.

MAP 2

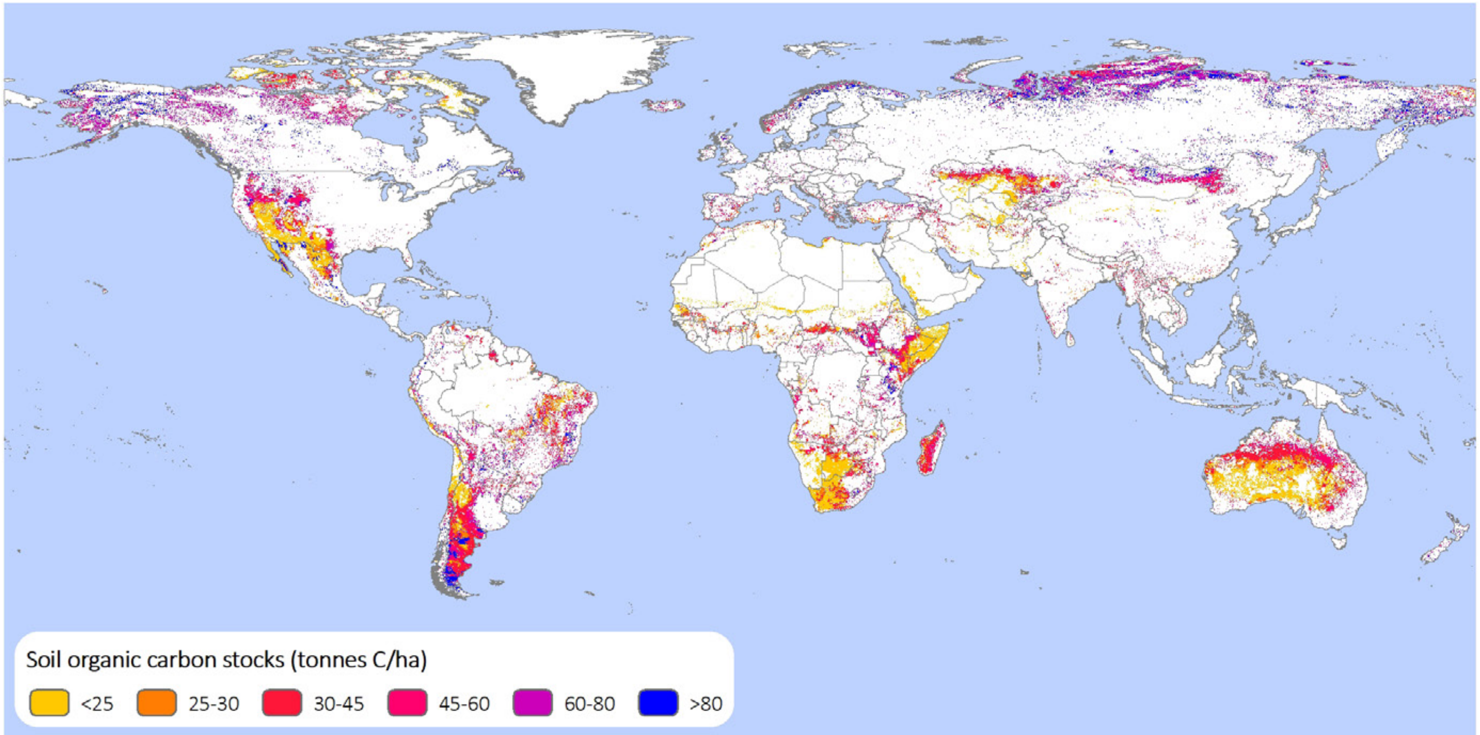
Baseline soil organic carbon (SOC) stocks (tonnes C/ha) in the top 30 cm in improved grasslands



Source: **United Nations Geospatial.** 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from Coleman and Jenkinson, 1996.

MAP 3

Baseline soil organic carbon (SOC) stocks (tonnes C/ha) in the top 30 cm in unimproved grasslands



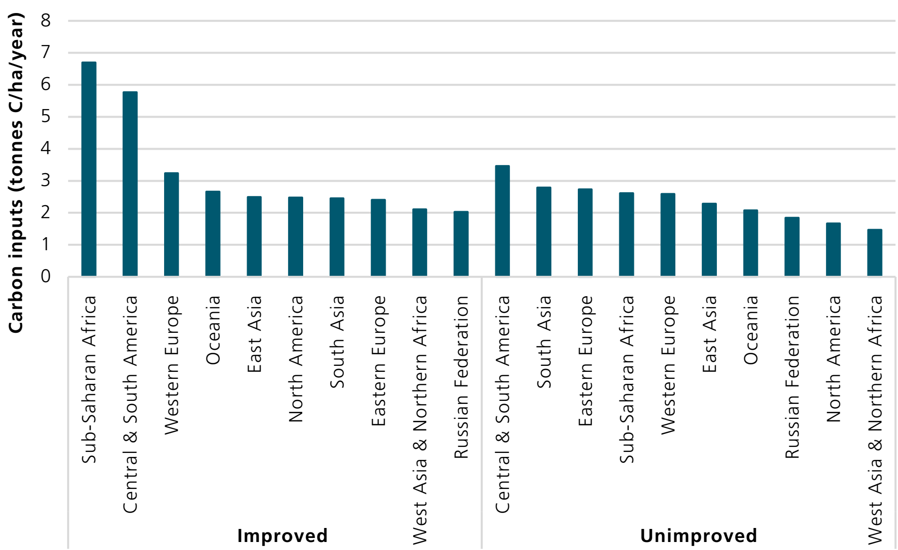
Source: **United Nations Geospatial.** 2020. *Map of the World*. United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from Coleman.

In improved systems, moderate amounts of SOC stocks were found in Central and South America, East Asia, and West Asia and Northern Africa, ranging from 52 to 56 tonnes C/ha. South Asia, Oceania, and sub-Saharan Africa regions have very low amounts of SOC, accounting for just 3.9 percent of the global total (Map 2).

In unimproved systems (Map 3) moderate amounts of SOC stocks were only found in Central and South America (49 tonnes C/ha), while in all other regions SOC stock level is lower than average global figures, ranging from 32 tonnes C/ha (sub-Saharan Africa) to 35 tonnes C/ha (South Asia).

Plant residues and animal manure also affect the SOC stocks. Globally, the average total yearly carbon input to the soil, for the reference baseline year 2010, was estimated to be 3.23 tonnes C/ha/year in improved systems. In the regions of sub-Saharan Africa and Central and South America, the total yearly carbon input to the soil was estimated to be higher than average figures, with values under improved grasslands reaching 6.7 tonnes C/ha/year and 5.8 tonnes C/ha/year, respectively (Figure 3). On the other hand, lower amounts of total carbon inputs to the soil were found in the Russian Federation (2.0 tonnes C/ha/year) and West Asia and Northern Africa regions (2.1 tonnes C/ha/year). The average total yearly carbon input to the soil, for the reference baseline year 2010, was estimated to be 2.35 tonnes C/ha/year in unimproved systems, with estimates close to the regional average of total organic carbon input of all world regions (Figure 3).

FIGURE 3
Regional average of total organic (plant and excreta) carbon input to the soil in unimproved and improved grasslands



Source: **UN**. 2020. *Map of the World*, modified with data from **Coleman, K. & Jenkinson, D.S.** 1996. RothC-26.3 - A Model for the turnover of carbon in soil. In: Powlson, D.S., Smith, P., Smith, J.U., eds. *Evaluation of Soil Organic Matter Models*. NATO ASI Series, 38: 237-246. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-61094-3_17

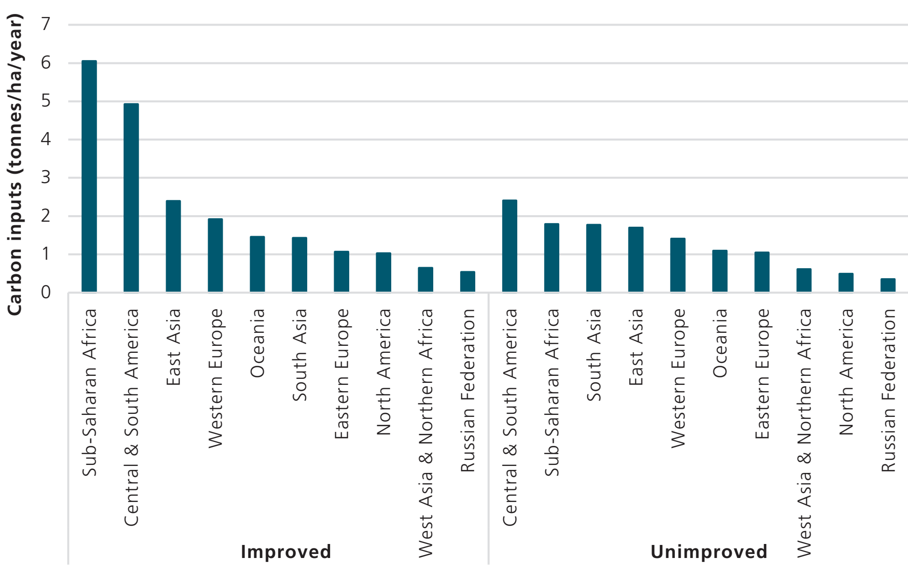
3.2 ASSESSMENT OF CURRENT CARBON STOCK LEVELS

Improved grasslands needed, on average, higher carbon inputs than unimproved systems to sustain current SOC stocks (2.1 vs 1.3 tonnes C/ha/year).

Some of the highest carbon input needs in improved systems were found in sub-Saharan Africa (6 tonnes C/ha/year), and Central and South America (5 tonnes C/ha/year). On the contrary, the Russian Federation, and West Asia and Northern Africa require low carbon inputs to the soil, with values below 1 tonne C/ha/year. The same regional distribution has been found in unimproved systems, with the Russian Federation requiring only 0.3 tonnes C/ha/year to maintain current levels of carbon in the soil, while parts of Central and South America need more than double the average required amount of carbon inputs (Figure 4).

Some of the highest carbon input needs were found in areas where high SOC stocks are associated with high mineralization coefficients related to the mild moist conditions, or with high SOC stocks and sandy soils. At the opposite end of the spectrum, other areas exhibited low carbon input requirements because of low SOC stocks and moderate to low mineralization levels. Therefore, the resulting global distribution of carbon inputs to maintain current levels of SOC stocks (Map 4) is strongly affected by the interaction of climate and current soil conditions.

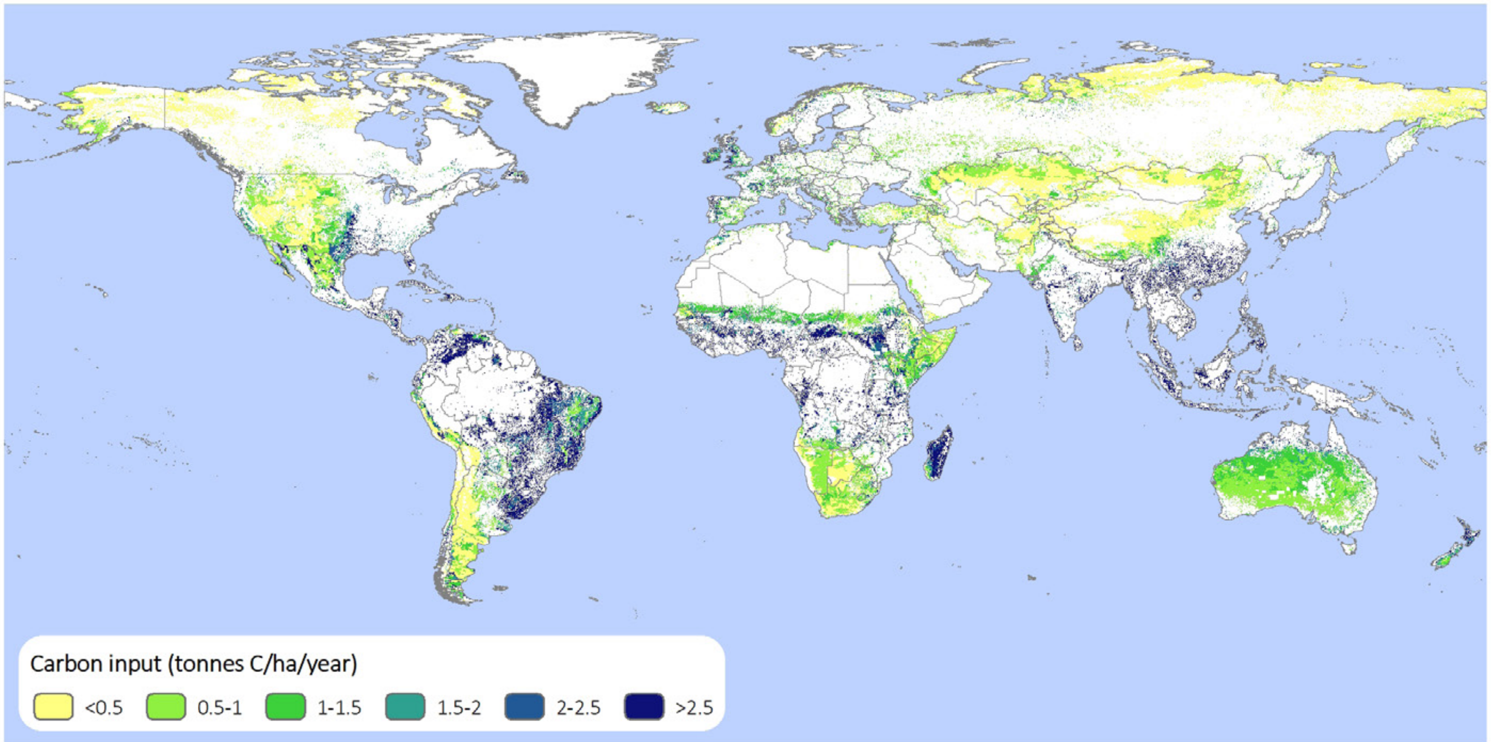
FIGURE 4
Regional averages of carbon inputs needed to maintain current levels of carbon in the soil in unimproved and improved grasslands



Source: **UN**. 2020. *Map of the World*, modified with data from **Coleman, K. & Jenkinson, D.S.** 1996. RothC-26.3 - A Model for the turnover of carbon in soil. In: Powlson, D.S., Smith, P., Smith, J.U., eds. *Evaluation of Soil Organic Matter Models*. NATO ASI Series, 38: 237-246. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-61094-3_17

MAP 4

Global carbon input levels (tonnes C/ha/year) needed to maintain current SOC stocks under improved and unimproved grasslands

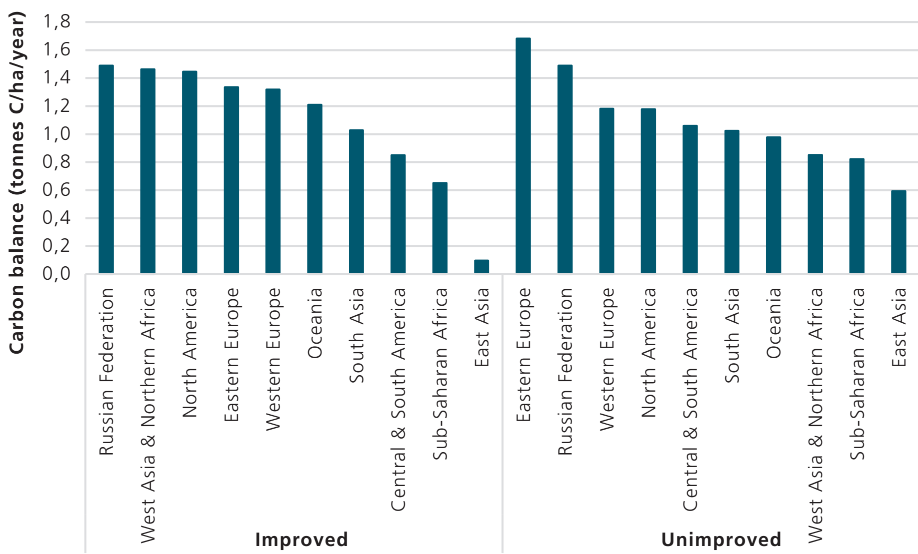


Source: **United Nations Geospatial.** 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from Coleman and Jenkinson, 1996.

In our framework, the estimated carbon inputs are those needed to maintain current SOC stocks at steady state. We compared the total carbon input (C_{Res} + C_{Exc}) to the estimated carbon inputs and the difference was termed the carbon balance (C_{bal}). The current carbon balance may be used to assess if current SOC stocks are increasing or decreasing. The majority of grassland soils seem to receive enough organic material to maintain current carbon stock levels. On average, C_{bal} in current grassland systems is 1.1 tonnes C/ha/year, for both improved and unimproved systems, hence indicating increasing SOC stocks.

At regional level, unimproved grasslands in Eastern Europe and the Russian Federation show the highest positive balances with values reaching 1.7 and 1.5 tonnes C/ha/year, respectively, while the lowest positive carbon balance (0.6 tonnes C/ha/year) was found in East Asia (Figure 5). Improved systems in the Russian Federation seem to follow the same pattern of the unimproved grasslands, with the highest C_{bal} of all regions (1.5 t C/ha/yr). On the other hand, we found that improved systems in East Asia are close to equilibrium conditions (0.1 tonnes C/ha/year), followed by sub-Saharan Africa (0.6 tonnes C/ha/year) and Central and South America (0.8 tonnes C/ha/year) (Figure 5).

FIGURE 5
Regional carbon balance (tonnes C/ha/year) for unimproved and improved grassland systems

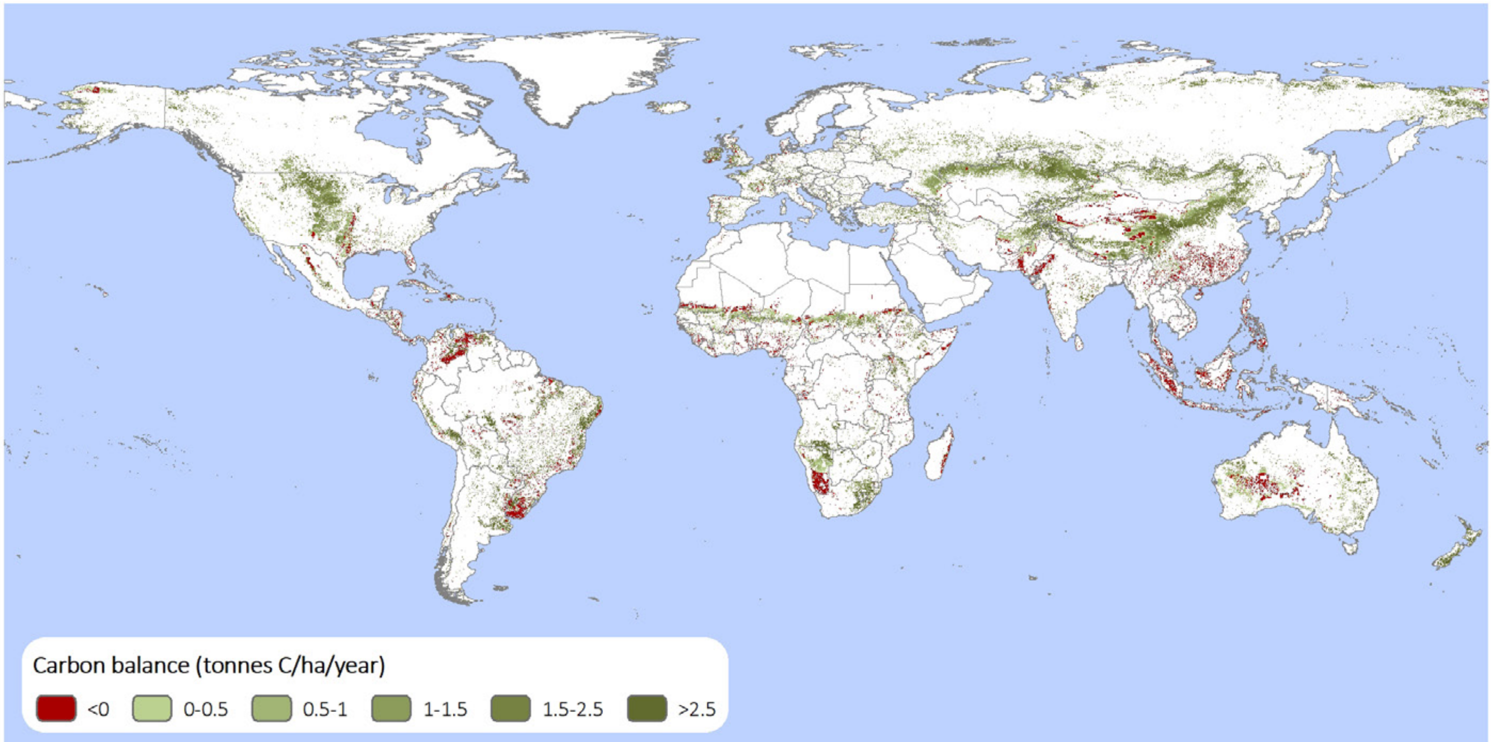


Source: **UN**. 2020. *Map of the World*, modified with data from **Coleman, K. & Jenkinson, D.S.** 1996. RothC-26.3 - A Model for the turnover of carbon in soil. In: Powlson, D.S., Smith, P., Smith, J.U., eds. *Evaluation of Soil Organic Matter Models*. NATO ASI Series, 38: 237-246. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-61094-3_17

However, it is important to note that for both grassland systems, several countries have a negative C_{bal}. Analysis indicated that available carbon inputs to the soil were lower than estimated carbon inputs needed to preserve current SOC stocks, and consequently were not sufficient to maintain stocks at steady state. In improved systems, the highest negative C_{bal} was found in Indonesia (-6.7 tonnes C/ha/year), the Philippines (-5.1 tonnes C/ha/year), Colombia (-4.5 tonnes C/ha/year), Malaysia (-3.9 tonnes C/ha/year) and Uruguay (-3.3 tonnes C/ha/year), meaning that current SOC stocks are likely to be decreasing due to anthropogenic stresses combined with climatic conditions (Map 5). Negative C_{bal} values were also found in unimproved systems in Colombia (-6.2 tonnes C/ha/year), Indonesia (-5.3 tonnes C/ha/year) and Mexico (-0.9 tonnes C/ha/year), among others (Map 6).

MAP 5

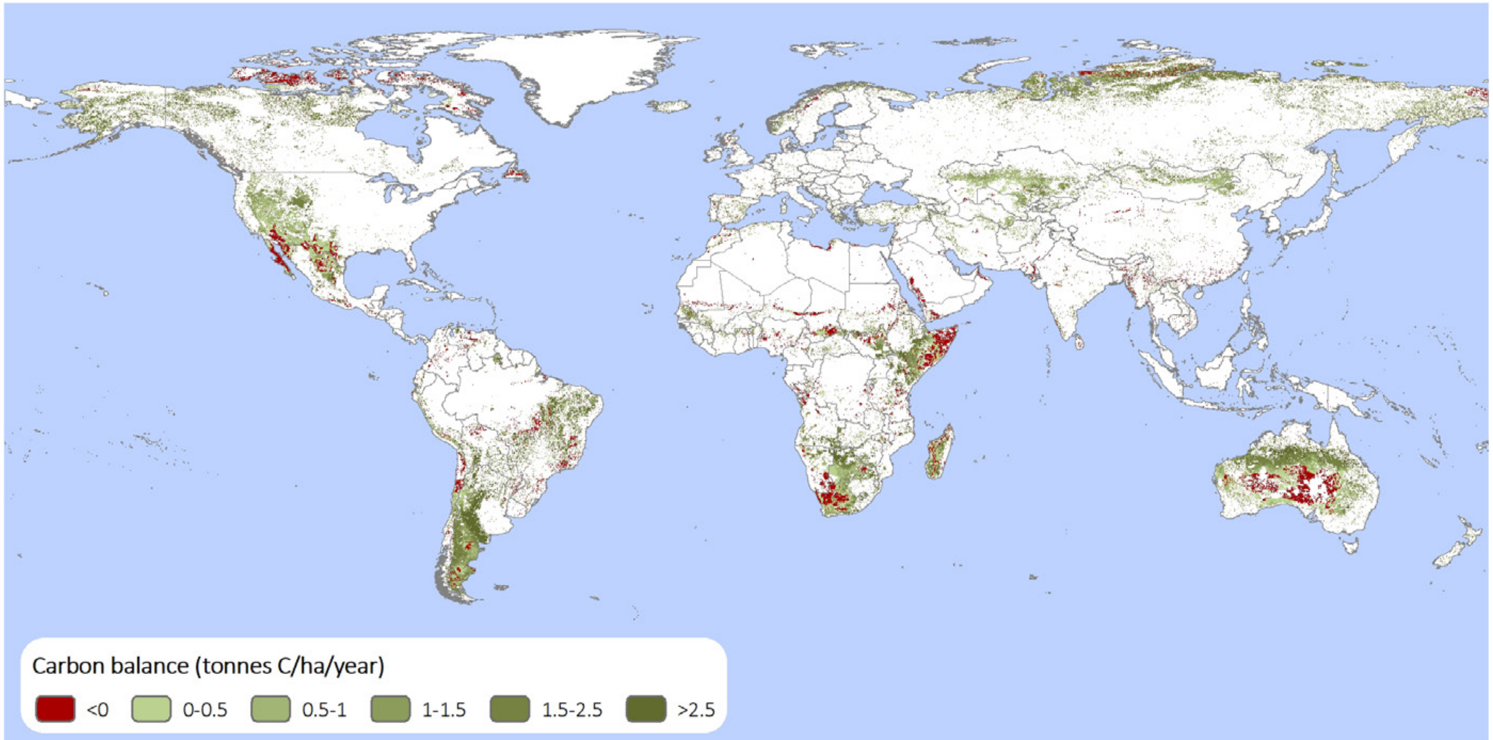
Carbon balance (tonnes C/ha/year) for improved grassland systems



Note: negative values indicate that current stocks cannot be maintained. Carbon balances were calculated under current climatic conditions.

Source: **United Nations Geospatial.** 2020. *Map of the World*. United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from Coleman and Jenkinson, 1996.

MAP 6
Carbon balance (tonnes C/ha/year) for unimproved grassland systems



Note: negative values indicate that current stocks cannot be maintained. Carbon balances were calculated under current climatic conditions.
Source: **United Nations Geospatial.** 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from Coleman and Jenkinson, 1996.

3.3 SOIL ORGANIC CARBON SEQUESTRATION POTENTIAL

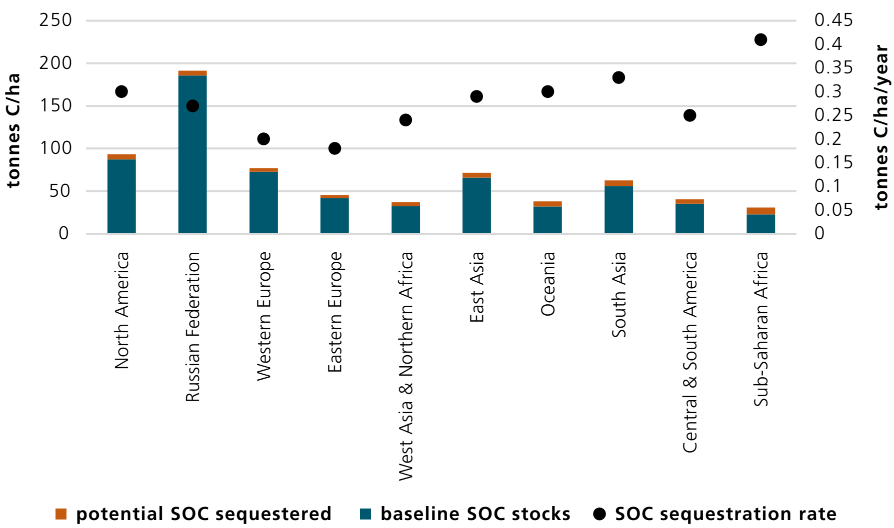
Estimates of global soil carbon stocks, trends and sequestration potential are now central to important topics, such as food security and climate change. In this context, regenerative forms of grazing can provide carbon removal from the atmosphere and storage in the soil. Well-adapted grazing systems – with improved pasture and optimized grazing regimes – have the potential to increase SOC on degraded grassland, or on grassland soils that have not reached their full carbon sequestration potential.

The Russian Federation showed the highest potential for carbon storage with an average SOC stock of 191 tonnes C/ha after 20 years of implementation of best management practices (Figure 6). However, soils of the Russian Federation are already fairly carbon-dense on average (186 tonnes C/ha) and these soils have likely reached their full sequestration potential, so even the best management practices will not provide a further accumulation of SOC.

The annual increment (on a per hectare basis) ranged from 0.18 to 0.41 tonnes C/ha across the various regions (Figure 6). Sub-Saharan Africa and South Asia show the highest potential for carbon storage on a per hectare basis (0.41 and 0.33 tonnes C/ha/year, respectively), followed by Oceania, North America, and East Asia. Western Europe and Eastern Europe have the lowest annual increments (0.20 tonnes C/ha and 0.18 tonnes C/ha respectively), which result in a negligible sequestration potential (Figure 6). In general, areas of the southern hemisphere with low carbon stocks show a large potential for soil carbon storage (Map 7).

FIGURE 6

Soil organic carbon (SOC) sequestration potential after 20 years of application of best management practices for all available grassland soils (i.e. those not excluded from the analysis as high SOC or sandy soils)

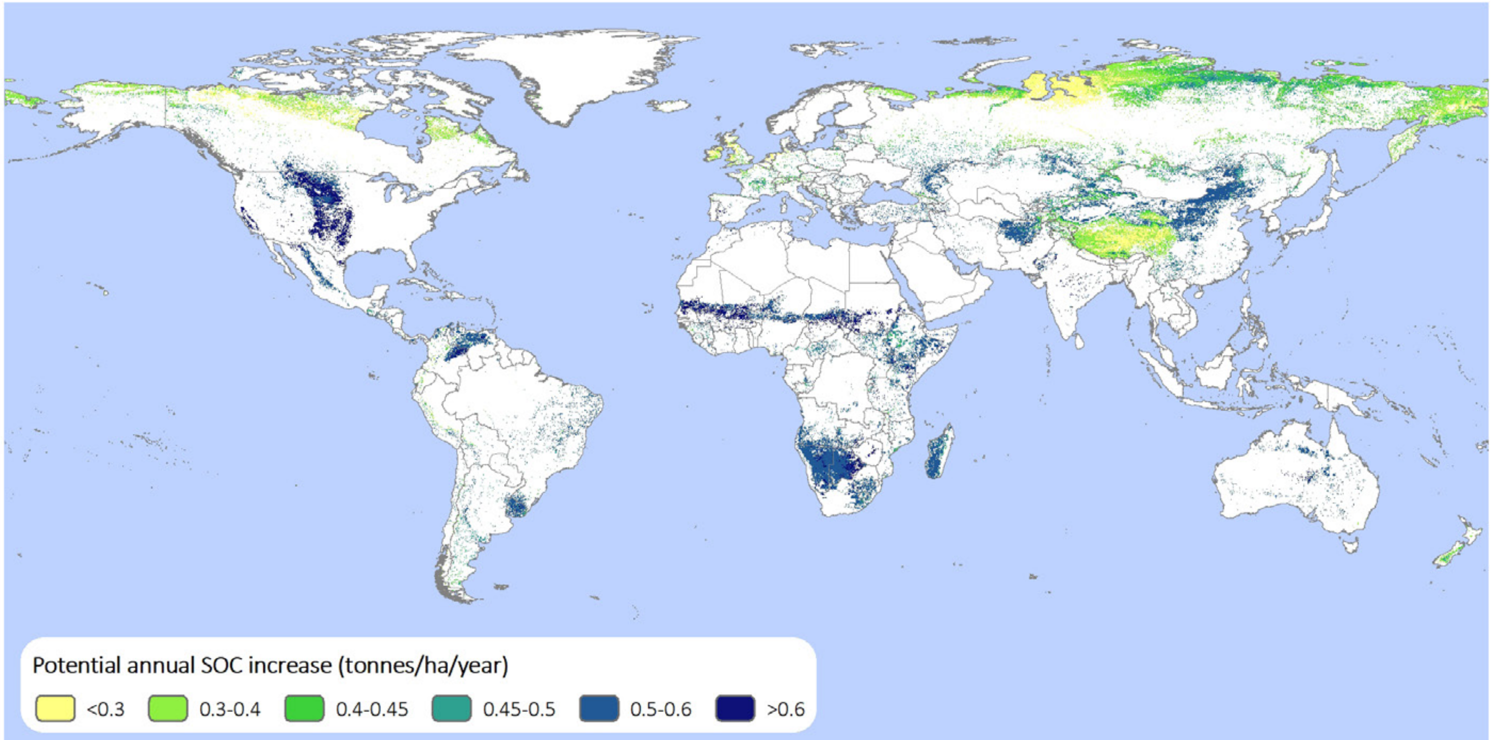


Note: Results are given by regional averages per hectare (bars) and their annual increment (dots)).

Source: **UN.** 2020. *Map of the World*, modified with data from Sommer, R. & Bossio, D. 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management*, 144: 83–87. https://doi.org/10.1016/j.jenvman.2014.05.017; **Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G. & Ruiperez Gonzalez, M.** 2014. SoilGrids1km — Global Soil Information Based on Automated Mapping. *PLOS ONE*, 9(8): e105992. https://doi.org/10.1371/journal.pone.0105992

MAP 7

Annual increase in soil organic carbon (SOC) in the top 30 cm on all available grassland soils globally (i.e. those not excluded from the analysis as high SOC or sandy soils)



Note: maps were produced based upon a geospatial analysis of datasets from the SoilsGrids250 database.

Source: **United Nations Geospatial.** 2020. *Map of the World.* United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from Sommer and Bossio, 2014 and Hengl *et al.*, 2014.

4. Discussion

4.1 BASELINE SOIL ORGANIC CARBON

In the year 2010 there was an estimated global annual uptake of 63.5 Mt of carbon in grassland soils to a depth of 30 cm, with unimproved systems storing slightly higher amounts than improved systems (33.8 vs 29.8 Mt C). Such a difference, even if small, is an expected result as unimproved systems are less managed compared to improved systems, with the latter more likely to lose carbon under human-induced activities. On average, the present study shows that in the year 2010 the SOC in global grasslands was about 51 tonnes C/ha to a soil depth of 30 cm (i.e. 53 tonnes C/ha in unimproved and 50 tonnes C/ha in improved systems). Grassland SOC stocks may be as low as 25 tonnes C/ha for herbaceous grasslands in deserts, and as high as 160 tonnes C/ha for evergreen shrub grasslands in boreal regions (Petri *et al.*, 2010; Lorenz and Lal, 2018). These results are comparable with our study, where we found SOC stocks of 25 tonnes C/ha, or lower, in regions with arid climate (Beck *et al.*, 2018) and higher SOC stocks, above 80 tonnes C/ha, in cold climates (Beck *et al.*, 2018). An early study from Sombroek and colleagues reported estimated SOC stocks of 124 tonnes C/ha to a 1 m soil depth (Sombroek, Nachtergaele and Hebel, 1993) in grasslands, while the Special Report on Land Use, Land-Use Change, and Forestry reported a soil carbon stock in temperate grasslands of about 236 tonnes C/ha to a 1 m soil depth (IPCC, 2019). A more recent meta-analysis by Dlamini, Chivenge and Chaplot (2016) estimated SOC stocks to 30 cm depth between 1 and 400 tonnes C/ha, with an average of 50 tonnes C/ha. Our study can be directly compared only with the latter study, which reported estimates to a soil depth of 30 cm. Despite the large SOC stock range, the average SOC stock values are comparable (i.e. 51 tonnes C/ha in our study vs 50 tonnes C/ha in Dlamini, Chivenge and Chaplot [2016]). Indeed, SOC stocks vary greatly among climatic regions and soil types, as reported in the few global studies focused on quantifying soil carbon in grasslands.

The results arising from the present study provide additional information on the SOC spatial distribution for both grassland systems. The greatest SOC stocks were found in temperate regions due to lower average temperatures compared to humid, subhumid, tropical, and semiarid regions resulting in lower decomposition rates, hence in the accumulation of SOC. Greater SOC stocks under wet climates could also be attributed to the high productivity of grasslands in wet environments. In comparison, the lowest SOC stocks were observed in arid to semiarid grassland soils due to the low rainfall amounts resulting in low biomass production and organic matter decomposition, hence a reduction of carbon inputs into the soil. Indeed, stabilization of SOC also depends on several soil properties such as soil pH, which contributes to regulating soil nutrient bioavailability, organic matter turnover and an array of soil processes (Kemmitt *et al.*, 2006), and soil clay and silt particles, which protect soil organic matter by stabilizing it against microbial mineralization (Six *et al.*, 2002). Climatic conditions explained much of the variability of SOC stock in grassland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soils to 30 cm depth, followed by the carbon input to the soil. In grassland systems, carbon inputs to the soil are associated with grass biomass production, grazing intensities and ruminant stocking density. In our framework, this parameter was derived from the GLEAM model, a tool that enabled comprehensive, disaggregated and consistent analysis of the environmental performance of global livestock production systems. The GLEAM model uses a herd model coupled with an IPCC (2006) Tier 2 approach to computing emissions, thereby enabling key characteristics of the livestock populations (e.g. herd structures, animal performance, rations and manure management) to be captured in the calculations. Further, GLEAM adopts a life-cycle approach and calculates the emissions arising along the supply chain from cradle to retail point. Finally, the reliance on geographical information systems (GIS) provides spatially explicit analysis and flexibility in combining datasets and aggregating results (MacLeod *et al.*, 2018). By 'soft-coupling' (i.e. a link between two individual models where a result of one model is integrated as an input parameter to the other model) GLEAM and RothC, it was possible to include detailed information about the contribution of livestock systems (e.g. N deposited, animal intake and distribution) to SOC stocks and to estimate the first spatially explicit baseline scenario for the year 2010. The results presented here are meant to provide an estimate of the SOC levels in grassland systems in 2010; such estimates are a starting point for further analysis, and in particular for designing and testing management practices that could be beneficial to mitigating climate change without compromising food security.

It is well known that among land-based GHG removal technologies, soil carbon sequestration practices play a role in delivering agroecosystem resilience, climate change adaptability, food security and improving nutrition. However, the effect of such practices should be analysed at local scale because local socio-economic constraints, legislation and environmental factors should be considered when designing interventions intended to mitigate climate change. Therefore, these results are intended to act as a baseline when identifying locations where interventions should be a priority (due to high soil degradation) and provide a baseline when quantifying the effect of such practices on soil carbon sequestration. Two case studies are presented in Box 1 and Box 2 to highlight the applicability of this framework at local level: to quantify changes in SOC stocks 30 years after the establishment of fodder gardens in East Africa (Box 1), and to assess the effect of pasture intensification in Paraguay (Box 2).

BOX 1

Assessing the effect of changing management practices on SOC case study Eastern Africa

The establishment of fodder gardens is a practice that results in high productivity under repetitive cutting, palatable fodder, and high protein content (20–25 percent). This practice provides firewood, is easy to establish, and also has the potential to improve soil quality through N fixation by legumes.

One tree species used in agroforestry systems that had remarkable success in conserving soil, nutrient cycling, and nutrient retention is calliandra (*Calliandra calothyrsus*). Calliandra, indigenous to Central America, is a small tree that reaches about 10 m in height, has a deep root system, and is an aggressive pioneer species, often found in disturbed areas such as roadsides, riverbanks and shifting cultivation plots (Palmer, Macqueen and Gutteridge, 1994). Calliandra grows naturally in moist, tropical regions up to an altitude of 1 500 m (Paterson, 1994), with annual rainfall between 700 and 3 000 mm, and annual temperatures ranging between 22 and 28 °C.

Because of the limited size of the farms, research focused on integrating the trees into existing cropping systems rather than on planting them in monoculture fodder banks. Farmers preferred planting trees in hedges around the farm compound, and in hedges along contour bunds.

In African countries, more than 40 000 smallholders (Kenya and Uganda) have established fodder gardens with calliandra as a practice to raise milk production, improve cow health and shorten the calving interval.

(Cont.)

Fodder trees require little or no cash investment or land taken away from producing food or other crops. The only inputs required are seeds and minimal amounts of labour. Moreover, this practice could provide other services, such as the provision of natural fencing, and erosion control (Kabirizi, Mpairwe and Mutetikka, 2004).

Despite the potential of this practice to provide several ecological and socio-economic benefits, little is known about its potential to sequester carbon in the soil. For this purpose, the RothC and GLEAM models were soft coupled to study the effect on SOC of the establishment of fodder gardens in mixed systems. GLEAM (v2.0) was run to estimate the N deposited under a business as usual (baseline) scenario, and a second run was performed to estimate the N deposited after the establishment of fodder gardens (intervention) in Eastern African countries (Ethiopia, Kenya, Uganda and the United Republic of Tanzania). Following the literature, 1 kg DM of calliandra was added to the diets of adult females producing milk in dairy cattle systems. The N deposited estimates for both the baseline and intervention scenarios were used as input to the RothC model to estimate the change in soil carbon 30 years after the establishment of fodder gardens (i.e. the RothC model was run for 30 years under baseline and intervention conditions). Under the two scenarios, all model inputs (i.e. weather, soil pH, soil bulk density and soil texture) were kept constant, except for the input from animal excreta. For both scenarios, N deposited was converted to carbon by applying a C:N ratio of 17.5 (FAO, 2015a) and used as input to the model runs.

Changes in SOC after 30 years of the application of fodder gardens were calculated as follows:

$$\Delta C = SOC_{INT} - SOC_{BAU}$$

Where ΔC is SOC change, SOC_{INT} is the SOC under the intervention scenario and SOC_{BAU} is the SOC under the baseline scenario.

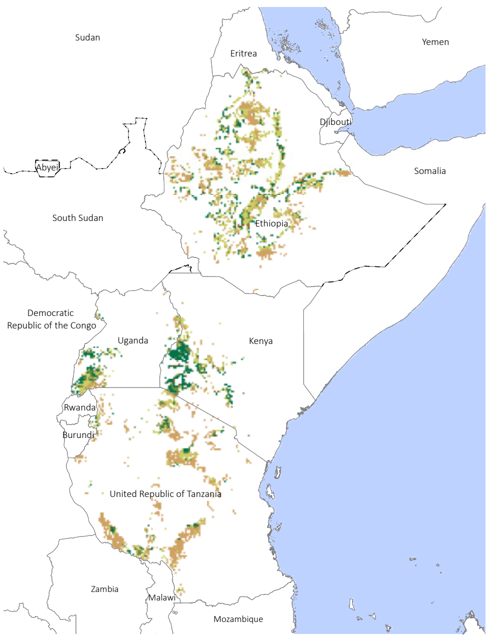
The estimated SOC stocks under BAU conditions in Eastern African grasslands range from 5.3 to 93.3 tonnes C/ha, with mean values of 40.9 tonnes C/ha. The mean SOC stock is in line with data presented by Tessema *et al.* (2020) in their review of SOC stocks and changes in grasslands in Eastern African countries. This metanalysis of local direct measurements of SOC reported a mean initial SOC stock of 43.8 tonnes C/ha, and a sequestration potential under grassland, following different management interventions, of 1.8 tonnes C/ha per year.

The RothC model estimated a potential increase in soil carbon – after the establishment of fodder gardens in mixed systems – of 0.9 tonnes C/ha, which leads to about 0.03 tonnes C/ha per year. This result is lower than the SOC potential reported by Tessema *et al.* (2020). It is, however, important to highlight that the two studies are not directly comparable due to the background information and assumptions used to determine the SOC potential.

(Cont.)

More specifically, in the publications by Tessema *et al.* (2020), eight different management practices were examined: enclosure, improved management (using rotations and adding different inputs such as manure, fertilizer, etc.), free grazing, light/heavy grazing, fencing, restoration measures, and conversion from natural forest to grazing. The intervention simulated by the RothC model is based on the establishment of fodder gardens with calliandra as a practice to increase milk production. The main changing factor applied to the modelling of soil carbon is the change in animal excreta, derived from a partial change in animal feed, with an application rate of 50 percent. The difference in carbon input between baseline and intervention is quite low (data not shown), however, even a small change in carbon input to the soil from animal excreta has the potential to increase carbon sequestration over 30 years. Other interventions and improved management practices, such as changing grazing intensity, could provide an even greater increase in SOC. It should be noted that calliandra could become invasive and cause ecological damage outside Central America; therefore, more studies are needed in the area to quantify the long-term impacts of such practices on soil health, as well as production and other ecosystem services.

Potential increase in soil carbon after the establishment of fodder gardens in mixed systems in Eastern African countries



Notes: Dashed lines on maps represent approximate border lines for which there may not yet be full agreement. Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined. Final status of the Abyei area is not yet determined.

Source: **United Nations Geospatial.** 2020. *Map of the World*. United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from Coleman and Jenkinson, 1996.

BOX 2

Assessing the effect of pasture intensification on SOC case study Paraguay

Over the last decades, despite heterogeneities at local scales, there has been overall a global trend of grazing systems intensification in response to increasing demand for livestock products and land competition. In Paraguay, increasing animal productivity is on the country's agenda, but environmental trade-offs should also be considered to define tailored interventions which will not compromise soil health and other ecosystem services. Therefore, it is crucial to explore the effect of pasture intensification on soil carbon dynamics. For this purpose, the RothC and GLEAM models were soft coupled to study the effect of pasture intensification on beef systems. GLEAM (v2.0) was run to estimate the N deposited under a business as usual (baseline) scenario; a second run was performed to estimate the N deposited after the intensification of grassland systems (intervention) in Paraguay. The following changes were made to the GLEAM inputs compared to the baseline scenario: feed intake was increased by 6.5 percent, biomass was increased by 10 percent and 90 kg/ha per year of synthetic N fertilizer was applied to the soil (N fertilizer was not applied in the baseline scenario). GLEAM estimates of N deposited for both baseline (BAU) and intervention (INT) scenarios were converted to carbon by applying a C:N ratio of 17.5 (FAO, 2015a) and then used as input to the RothC model to estimate the change in soil carbon after 30 years of pasture intensification. To do so, the RothC model was run for 30 years for both BAU and INT conditions. Between the two scenarios, all other model inputs (i.e. weather, soil pH, soil bulk density and soil texture) were kept constant.

Changes in SOC after 30 years of pasture intensification were calculated as follows:

$$\Delta C = SOC_{INT} - SOC_{BAU}$$

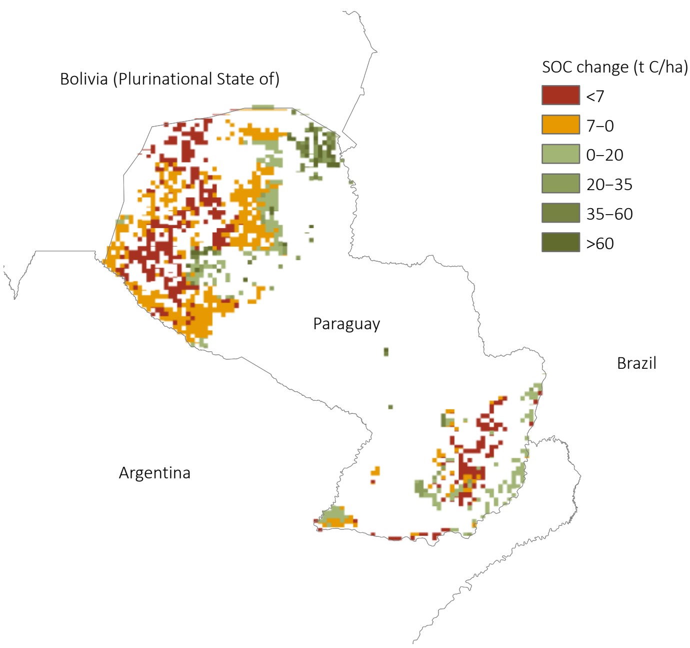
Where ΔC is SOC change, SOC_{INT} is the SOC under the intervention scenario and SOC_{BAU} is the SOC under the baseline scenario.

The RothC model estimated a mean potential SOC increase of 27 tonnes C/ha after 30 years of pasture intensification in Paraguay, which corresponds to a yearly accumulation of about 0.9 tonnes C/ha in the soil. However, changes in SOC differ substantially across the country, with accumulation reaching 150 tonnes C/ha in the northeast of the country. A substantial depletion in SOC is found in the north/northwest, with a maximum loss of about 50 tonnes C/ha. Areas with positive change in SOC experience an accumulation of carbon in the soil mainly because of the higher carbon inputs to the soil from both plants and animals, compared to the baseline scenario. In this case, synthetic N fertilizer does not inhibit SOC accumulation, a process that is likely to occur in areas where animal density is low and not enough organic material is returned to the soil from animal excreta.

(Cont.)

Increasing SOC stocks under perennial grasses relies mainly on enhancing carbon inputs from plant roots and residues. This can be achieved by managing plant biomass removal from grazing or increasing forage production through improved species, irrigation and fertilization, yielding increases in SOC stocks of as much as 10 percent (Conant *et al.*, 2017). In our study, fertilization, yield and animal feeds were increased compared to the baseline scenario. As a result, we estimated an increase in SOC of 0.9 tonnes C/ha a year, which leads to an increase in SOC stocks of about 7 percent. This increase is, however, only achievable in areas where initial soil conditions, soil nitrogen and animal density are balanced, otherwise a depletion of carbon will occur. Soil carbon is only one component of the carbon balance system. Pasture intensification, achieved by increasing fertilization, yield and animal feeds, has a large impact on methane emissions and other GHG fluxes. Therefore, for a full system budget, it is imperative to include estimates of changes in methane emissions following pasture intensification in order to understand the environmental impacts of such an intervention on the full system.

Potential soil organic carbon (SOC) change (tonnes C/ha) after 30 years of pasture intensification



Source: **United Nations Geospatial.** 2020. *Map of the World*. United Nations. Cited 22 August 2022. www.un.org/geospatial/file/2285/download?token=puayKYRA modified with data from Coleman and Jenkinson, 1996.

It should be noted that the framework presented here, as well as the SOC stock estimates, follow the approach described in the LEAP guidelines for SOC assessment and the GSOC-MRV Protocol, a FAO protocol for measurement, monitoring, reporting and verification of SOC in agricultural landscapes (FAO, 2020b). However, several assumptions have been used to generalize and simplify the methodology to be applied globally. Moreover, datasets on soil, climate and carbon inputs (at both regional and global levels) carry levels of uncertainty that should not be disregarded when applying this framework and the SOC stock baseline estimates to analyze mitigation strategies. A detailed description of the model uncertainties is given in section 4.5.

4.2 SOIL ORGANIC CARBON BALANCE

Different methods have been used to estimate carbon input to the soil for modelling purposes. They range from inverse modelling and allocation functions to expert opinion. The diversity of methods and contexts results in a great variety of estimates (Martin *et al.*, 2021). In our study we estimated carbon inputs in two ways: by IPCC Tier 2 methodology using the GLEAM model to quantify the actual input to the soil; and by inverse modelling to determine the carbon inputs needed to maintain current levels of SOC stocks. Overall, estimated carbon inputs presented here were in line with other estimates found in the literature using the RothC model, which ranged from 1.18 (Xu, Liu and Kiely, 2011) to 5.2 tonnes C/ha/year (Meersmans *et al.*, 2013) for grasslands.

When estimated using an inverse modelling approach, the calculation of these carbon input levels results from the interplay between observed SOC stocks, the SOC mineralization rates and the quality of the incoming organic matter (i.e. plant residues and organic amendments). Unimproved grasslands needed either less carbon input or fewer carbon inputs than improved systems to maintain current SOC stocks. This might be explained by the fact that unimproved grasslands are mainly located in high altitude regions with lower soil organic matter mineralization rates due to lower temperatures as compared to other warmer areas, and also by the quality of incoming plant material which has to be specified in inverse modelling approaches. Martin *et al.* (2021) found the same result for French grasslands using the same methodological approach used in this study.

The FAO Synthesis Report on the State of the World's Land and Water Resources for Food and Agriculture (FAO, 2021) reports that about 13 percent of grassland area is degraded due to high anthropogenic pressure, which is driven by: agricultural expansion, deforestation, fire extent and frequency, grazing density, population density, and ratio of invasive/native species. Another 34 percent of the global grassland area has reduced biophysical status and it is defined as deteriorated. Soil organic carbon is a factor influencing land deterioration, but other drivers, such as water erosion rate, wind erosion, water stress, native species richness and above-ground biomass contribute to the overall biophysical status of land. Interestingly 54 percent of the grassland area is reported to be in a stable condition (FAO, 2021). Our global estimates on the state of carbon in grasslands show that grasslands were, on average, close to equilibrium (1.09 tonnes C/ha/year for improved and 1.27 tonnes C/ha/year for unimproved grasslands). Positive C_{bal} values were found in areas where the land is stable or even under improved biophysical conditions, such as grasslands in the United States of America, Kazakhstan and Mongolia. These are areas under low human-induced pressure on land (FAO, 2021). The highest negative C_{bal} was found in East Asia, Central and South America, and Africa south of the Equator, meaning that current SOC stocks are likely to be decreasing due to anthropogenic stresses combined with climatic conditions (Map 4). This is in accordance with the latest Synthesis Report on the State of the World's Land and Water Resources for Food and Agriculture (FAO, 2021), which identifies these regions as severely affected by soil degradation (FAO, 2021). Most grasslands at risk of human-induced land degradation are exposed to decreasing freshwater availability. There are exceptions in Southern America and sub-Saharan Africa, where decreasing land productivity and soil protection account for declining ecosystem services. In Asia, increasing water stress contributes to grasslands at risk. In sub-Saharan Africa, grasslands are prone to frequent and intense fire (FAO, 2021).

It is noteworthy that no specific global measurements are currently available, and that the diversity of situations – in terms of climate, soils and management practices – might have been crucial for soil carbon dynamics in these areas, as evidenced by the variability of the carbon input values in grassland systems (Figure 3).

4.3 GRASSLAND POTENTIAL TO SEQUESTER SOIL CARBON

Increasing SOC in grassland areas globally is less likely than on croplands which are already intensively managed (Smith *et al.*, 2008). However, the adoption of improved management practices on grasslands offers the opportunity to sequester significant amounts of carbon in the near term, contributing to global mitigation efforts and restoring degraded lands. The 4 per 1000 (4p1000) initiative has identified an aspirational sequestration target of 3.5 Gt C/year to provide substantive global mitigation. Our estimates suggest that about 17 percent of this target could be reached in the top 30 cm of grassland soils alone by enhancing management through the incorporation of organic manures, some types of agroforestry practices, or rotational grazing. However, it is important to note that we used an empirical approach to determine the increase in percent-SOC in response to improved management, but specific management practices have not been tested. We attempted to do so for two case studies, by applying the RothC model in East Africa (Box 1), and Paraguay (Box 2), but more work is needed to understand the impact of individual practices at global scale.

Our statistical estimate of soil carbon sequestration potential is one of the first attempts at providing a detailed, spatially-disaggregated assessment at global level. Petri *et al.* (2010) integrated demographic data with GIS to calculate potential per capita carbon sequestration and estimate the potential for land managers to engage in mitigation sequestration schemes while using the land for their livelihoods. In their study, Petri *et al.* (2010) calculated the SOC potential after 20 years by applying sequestration factors for organic carbon as a function of grassland typology, management status and climatic zones. Results are given for climate and grassland types and the usage of different data sources makes it difficult to compare against our estimates by continent. Globally, Petri *et al.* (2010) estimated a SOC change of about 1.5 tonnes C/ha/year, which is somewhat higher than our conservative estimates of 0.29 tonnes C/ha/year. This is mainly due to the high sequestration factors used for estimating organic carbon sequestration after 20 years. In our study, we used a global value of percent increase in SOC, which results in lower SOC potential compared to the estimates reported by Petri *et al.* (2010). The spatial distribution of available grassland soils is also different in the two studies. In calculating the SOC potential, highly organic soils and sandy soils were excluded from the analysis, resulting in a reduced area studied and lower SOC potential compared to other published estimates (Petri *et al.*, 2010). The recently published Global SOC sequestration potential (GSOCseq) map (FAO, 2022) reports a mean sequestration rate of 0.19 tonnes C/ha/year in grasslands under a sustainable management scenario which implies a 20 percent increase in C inputs over a 20-year period. Our empirical approach is based on the assumption that the carbon concentration in the soil would increase by 0.27 percent if management practices known to improve SOC sequestration would be applied over a 20-year period worldwide. Due to this preliminary assumption, our estimates are slightly higher than the GSOCseq estimates for grasslands.

It should be noted that the estimated SOC sequestration potential, and its spatial distribution, is strictly dependent on the initial soil conditions (e.g. soil bulk density and texture), but estimates do not account for differences in climate and important soil process issues, such as carbon input and turnover rate. However, there is no published work specifically dedicated to the prediction of soil carbon sequestration potential in grassland by process-based modelling. Indeed, the RothC model (Coleman and Jenkinson, 1996) has been previously used to estimate the likely responses of soils to future climate and interactions with projected future land-use changes (Gottschalk *et al.*, 2012). A recent study conducted by Morais, Teixeira and Domingos (2019) calculated global SOC dynamics for 80 specific land uses within broad land-use classes (e.g. cropland, forest and grassland). Nevertheless, estimates of SOC sequestration potential on grassland are still uncertain, and often included in vast assessments, hence disentangling grassland impact on SOC sequestration appears challenging.

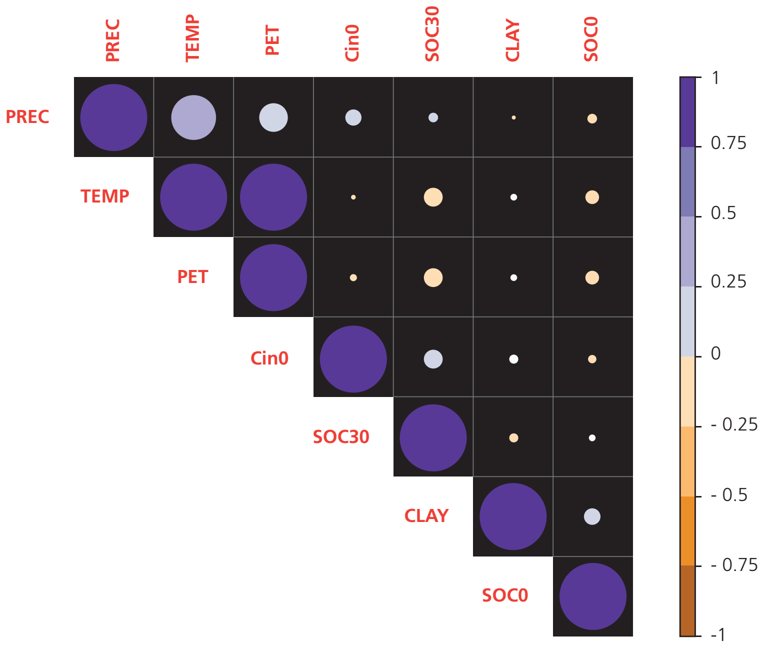
In this study, a simple statistical approach was applied to obtain a first estimate of attainable SOC sequestration rates in grasslands, identifying regions with greater potential to sequester carbon after implementing management practices. It provides a general framework for countries with limitations on implementing more complex, intensive data requiring, process-oriented modelling approaches.

4.4 SOURCES OF UNCERTAINTIES REGARDING THE BASELINE SOIL ORGANIC CARBON STOCKS

The results of the statistical analysis of all variables driving the RothC model show that the modelled SOC stocks are correlated to climatic conditions (e.g. temperature and potential evapotranspiration). This is an expected result as meteorological conditions directly affect soil processes, such as mineralization rates, and indirectly affect the amount of organic material (mainly plant residues) entering the soil. Moreover, modelled soil carbon is positively correlated to carbon inputs (Figure 7). This is also an expected result as inputs from plant residues and manure are the main external sources of carbon entering the soil, which will be stored in the soil depending on clay and climatic conditions.

In this study, analyses were performed to test the sensitivity effect of three main input variables on the baseline SOC stocks. The input variables tested were initial SOC stocks, carbon inputs and air temperature (i.e. those with higher correlation with the modelled SOC stocks). The relative change (percent) was calculated for four scenarios, as shown in Table 2.

FIGURE 7
Correlation matrix of main variables used to drive the RothC model



Note: (SOC0=initial SOC, SOC30=Soil Organic Carbon at the end of the 30 years model run (baseline SOC), PET= potential evapotranspiration, TEMP=temperature, PREC=precipitation, Cin0= organic carbon input to the soil).

Source: **UN.** 2020. *Map of the World*, modified with data from Sommer, R. & Bossio, D. 2014. Dynamics and climate change mitigation potential of soil organic carbon sequestration. *Journal of Environmental Management*, 144: 83–87. https://doi.org/10.1016/j.jenvman.2014.05.017; **Hengl, T., de Jesus, J.M., MacMillan, R.A., Batjes, N.H., Heuvelink, G.B.M., Ribeiro, E., Samuel-Rosa, A., Kempen, B., Leenaars, J.G.B., Walsh, M.G. & Ruiperez Gonzalez, M.** 2014. SoilGrids1km — Global Soil Information Based on Automated Mapping. *PLOS ONE*, 9(8): e105992. https://doi.org/10.1371/journal.pone.0105992

TABLE 2
Sensitivity analysis of model results (SOC stocks) to changes on main variables used to drive the RothC model

Variable	Scenario	Relative change
Carbon inputs	- 50% of initial carbon inputs	-28.8%
	- 20% of initial carbon inputs	-11.5%
	+ 20% of initial carbon inputs	14.4%
	+ 50% of initial carbon inputs	28.8%
SOC stocks	- 50% of initial SOC stocks	-21.2%
	- 20% of initial SOC stocks	-8.5%
	+ 20% of initial SOC stocks	10.6%
	+ 50% of initial SOC stocks	21.3%
Air temperature	Initial temperature +2 °C	-18.1%
	Initial temperature +1 °C	-23.2%
	Initial temperature -1 °C	34.9%
	Initial temperature -2 °C	41.5%

The results showed that carbon input variability leads to ±30 percent change in the baseline SOC stocks, while changes in initial SOC stocks had a relative change from the baseline SOC stocks of about ±20 percent. Increasing air temperature will negatively impact the baseline SOC stocks, with a relative change of up to -23.2 percent, while a decrease in air temperature will have a relative change of up to 41.5 percent.

These results show that the major contributor to baseline SOC stock uncertainty is the variability in carbon inputs. In this study, the plant residue inputs to the soil were estimated from the dry matter yield estimates (Haberl *et al.*, 2007), and animal excreta was derived from the deposited nitrogen simulated by the GLEAM 2.0 model. Both datasets carry some uncertainties; for instance, the above-ground dry matter is estimated from NPP, which in turn can be estimated through various principles (e.g. light use efficiency, plant growth, satellite information). To reduce uncertainties about soil carbon inputs, and therefore on SOC estimates presented here and elsewhere, it is crucial to generate local datasets and explore new and existing NPP datasets in order to improve the accuracy of plant residue estimates. In addition to intrinsic methodological differences among different NPP products, differences in land use definition and distribution contribute to the large uncertainty associated with carbon input estimates from plant residues.

Soil carbon inputs from animals have been estimated by applying a C:N ratio (from literature; see FAO, 2015a) to the N deposited. In this study, the C:N ratio was derived from the literature as a global average value, and as such it could differ from regional figures. However, it was observed that the sensitivity of the RothC model to animal excreta quality is low (between 1.1 percent and 3 percent) (Jebari *et al.*, 2020), so this variable does not impact the SOC stocks modelled by RothC. The quantity of carbon entering the soil from animal excreta impacts the SOC results. In this study, this variable was derived from GLEAM estimates of deposited N, which follows a Tier 2 approach from IPCC (2006). In addition to intrinsic methodological uncertainties linked to such an approach, which are extensively discussed in Opio *et al.* (2013), it is important to note that diversity in land maps and definitions affects the quantification of N indicators (Kaltenegger *et al.*, 2021). Moreover, grassland definition and distribution affect all underlying input data and therefore exacerbate the uncertainty of the model results. In general, the ability to accurately estimate carbon inputs to the soil is crucial in modelling soil processes and can be a major source of uncertainty, as shown here and elsewhere (Hashimoto, Wattenbach and Smith, 2011; Neumann *et al.*, 2015; Martin *et al.*, 2021).

Maps of soil properties are also known to carry a significant uncertainty due to the limited freely available soil data needed to calibrate the statistical models used to derive maps. In the statistical analysis of model sensitivity to input variables, the SOC stocks used to initialize the model significantly affected modelling results. A comparison of three soil datasets, namely SoilGrid (Hengl *et al.*, 2014), HWSD (FAO, IIASA, ISRIC, ISS-CAS & JRC, 2012), which we used in this study, and the Northern Circumpolar Soil Carbon Database (Hugelius *et al.*, 2013) was conducted by Tifafi, Guenet and Hatte (2018) to quantify differences in soil properties among datasets, and to evaluate them against soil data from the United States of America, England, Wales and France. The results of this comparison highlighted that global SOC stocks predicted by each product differ greatly, particularly for boreal regions where differences can be related to large disparities in SOC concentration.

Differences in other regions were mainly related to differences in soil bulk density estimates. When comparing the three datasets versus ground truth data, a significant difference in spatial patterns was found, with an underestimation in SOC stocks of more than 40 percent compared to field data. The HWSD and SoilGrid maps were also compared globally against the GSOCmap, the first global SOC map ever produced through a consultative and participatory process involving member countries (FAO and ITPS, 2018). A larger agreement between the GSOCmap and the HWSD than between the GSOCmap and the SoilGrids was found. Positive and negative changes from the GSOCmap and the HWSD were irregularly distributed, but the changes from the GSOCmap to the SoilGrids tended to be positive, suggesting a major carbon pool predicted by the latter product (FAO and ITPS, 2018). The estimation of the global soil carbon stock is still quite uncertain, and improved geostatistical methods are urgently needed to reduce the propagation of such uncertainties on soil models. Moreover, soil and land-use distribution datasets are not linked and are often produced on different timescales. This can lead to the allocation of initial SOC stocks to a land-use that does not reflect the current condition.

The uncertainty regarding initial SOC stocks, and their distribution and allocation to different land uses, together with model uncertainties, should be carefully taken into consideration when using the results of this work on the current state of carbon in the soil and its potential to be sequestered in grassland systems.

5. Conclusions and way forward

Soils contribute to the achievement of the UN SDGs through carbon sequestration. By enhancing soil health and fertility, soils can play a crucial role in climate action (target 13.2), land degradation neutrality (target 15.3), and alleviating hunger (targets 2.1 and 2.4). Despite the undeniable technical potential to sequester carbon in soils, there are often significant limitations to achieving that potential in any particular location and within specific production systems.

The present study provides a spatially explicit report on the state of grassland soils, with estimates of the SOC stocks for the year 2010. On average, in the year 2010, the SOC in global grasslands was about 51 tonnes C/ha to a soil depth of 30 cm, with minor differences between improved and unimproved systems (53 vs 50 tonnes C/ha). The SOC stocks presented in this report can be used as a baseline for future work to explore the impacts of livestock management on soil carbon at country and farm levels. However, there is still a strong necessity for additional data on current soil conditions, especially from underrepresented regions. The approach used to develop the SOC baseline for grasslands follows the methodology recommended by the Global Soil Partnership (GSP) for measurement, monitoring, reporting and verification of SOC in agricultural landscapes (FAO, 2020b). Examples of practical application of our SOC stock estimates at national level, including specific interventions, have been given in Box 1 and Box 2. A recent review of 184 countries' initial NDCs, found that only twenty-eight countries referred to SOC in their NDCs (Wiese *et al.*, 2021). Countries' reasons for not including SOC in NDCs included the need to prioritize goals of sustainable development and food security above climate mitigation, a lack of incentives for farmers to improve management practices, and the difficulty of accurately monitoring changes in SOC. The results of this report could therefore support the inclusion of SOC targets in NDCs, which will improve NDCs' comprehensiveness and transparency for tracking and comparing policy progress across NDCs.

The majority of grassland soils seem to receive enough organic material to maintain current carbon stock levels. However, improved grasslands needed, on average, higher carbon inputs than unimproved systems to sustain current SOC stocks (2.1 vs 1.3 tonnes C/ha/year). The positive soil carbon balance found in both improved and unimproved systems globally indicates a potential increase in SOC stocks. Despite such a positive trend globally, the large spatial variability of these estimates highlights that the soil state at country level could differ greatly from the global estimates. Fifty-four percent of the grassland area is reported to be in a stable condition (FAO, 2021); our global estimates support this finding, showing positive carbon balance in areas where the land is stable or even under improved biophysical conditions. On the other hand, negative carbon balance was found in East Asia, Central and South America, and Africa south of the Equator, meaning that current SOC stocks are likely to be decreasing due to anthropogenic stresses combined with climatic conditions. The findings of this analysis show that there is room for additional

carbon storage in some grassland soils. The main recommendations for grassland systems are to prioritize carbon returns in deteriorated soils that have a negative carbon balance, and to protect SOC in areas – particularly under unimproved grasslands – with high carbon stocks. Grasslands could contribute to the recarbonization of degraded land and the results of the present study can highlight hotspots where interventions on grasslands are needed to preserve or increase SOC in the long term.

The empirical approach used in this study made it possible to estimate the soil carbon sequestration potential of available grasslands following the application of management practices known to improve SOC sequestration or protection. Grasslands could sequester 0.3 tonnes C/ha/year in the 0–30 cm depth layer, which could be an important contribution to global mitigation efforts. The adoption of improved management practices offers the opportunity to sequester significant amounts of carbon in the near term, and potentially to make an important contribution to global mitigation efforts. The 4p1000 Initiative has identified an aspirational sequestration target of 3.5 Pg C/year to provide substantive global mitigation. Our estimates suggest that 17 percent of this target could be reached in the top 30 cm of grasslands and continue over at least 20 years after adoption of SOC enhancing management, such as the incorporation of animal manures, agroforestry and rotational grazing. This requires that grasslands increase SOC storage between 0.18–0.41 tonnes C/ha every year. Our estimates do not account for differences in climate and important soil process issues, notably nutrient and water limitations, biomass production and turnover rates. However, sequestering carbon via increases in the soil component on grasslands is an achievable and potentially effective route to quickly increasing CO_2 sequestration in the near term. Despite the large technical potential to sequester carbon in soils, there are often significant limitations to achieving that potential in any particular place and within specific farming systems. In addition, there may be trade-offs with productivity, food security or hydrologic balances, as well as concerns regarding other GHGs, such as N_2O.

A full system analysis requires estimates of GHG emissions alongside SOC estimates, or else misleading messages could arise from the investigation of independent components of the system balance. The methodology presented here made it possible to assess SOC stocks by soft-coupling the RothC soil carbon model with the GLEAM LCA model. Specifically, the GLEAM model provided inputs which have been used to drive the soil model. Future work should target including soil carbon estimates in full LCA studies. The main challenges would be to develop a methodology to allocate SOC stocks to different livestock units and to account for temporal dynamics of carbon in the soil. Nevertheless, the addition of a soil carbon compartment in the GLEAM model will enable accurate life cycle assessment in livestock systems as well as the design of targeted national policies for climate change mitigation and food security through the livestock sector.

Potential users should take into consideration the uncertainties deriving from the underlying datasets and the limitations of the approaches used to produce the SOC estimates. In this context, future technical work should focus on testing the impacts of different data sources on the SOC estimates. In particular, newly published soil carbon maps, such as the global SOC map (FAO and ITPS, 2018), and spatial data infrastructure such as the Global Soil Information System (GLOSIS), could be used to refine global SOC stocks estimates. GLEAM's forthcoming update on livestock LCA analysis for the year 2015 will also be a useful tool to acquire newer information on organic inputs to the soil, which could be used as a driver for the soil model. In general, the use of alternative sources of all major inputs used to estimate SOC stocks would be required to quantify model uncertainties and to observe SOC stock changes over time.

The results arising from the present work provide a global overview of the state of soil carbon in grasslands, and their potential to sequester carbon in the soil. The SOC stocks and changes have been analysed to a soil depth of 30 cm. However, SOC can also be stored at deeper soil layers and future work should aim to both refine current estimates as well as develop new approaches to predict SOC in deep soil layers. Moreover, there is still a significant need for additional data, especially from underrepresented regions (Merbold *et al.*, 2021), on current soil conditions, and on the effects of management practices on SOC stocks and GHG emissions. Involving local experts and institutions is a fundamental step for modelling improvements as well as knowledge exchange. In this context, the GSP partnership has recently published the first ever country-driven global SOC sequestration potential (GSOCseq) map (FAO, 2022). The GSOCseq map was developed based on the submissions of national experts appointed by FAO Member Nations. A bottom-up approach was used to establish a reliable, transparent and cost-effective mechanism to monitor, report and verify changes in SOC stocks in agricultural areas. The methodology used is based on the RothC model and it is constantly extended, improved and updated to better characterize local SOC dynamics. The FAO LEAP and GSP partnerships are actively collaborating to improve the GSOCseq map and methodology in order to better characterize soil carbon dynamics in grasslands by refining the definition of grassland (e.g. to include improved and unimproved grasslands) and the sustainable soil management scenarios currently used in the GSOCseq map.

The work presented here represents a first step to quantify the state of grassland soils, as well as to identify and prioritize areas with potential to increase SOC stocks through SOC sequestration in order to enable accurate life cycle assessment of livestock systems as well as the development of targeted livestock sector-driven national policies for climate change mitigation and food security.

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Corrigendum

23 February 2023

The following corrections were made to the PDF of the report after it went to print.

Page	Location	Text in printed PDF	Text in corrected PDF/ Notes
9	Full page	The global map excludes some countries	The global map contains all the countries
17	Full page	The global map excludes some countries	The global map contains all the countries
18	Full page	The global map excludes some countries	The global map contains all the countries
21	Full page	The global map excludes some countries	The global map contains all the countries
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This report presents the estimation of the baseline soil organic carbon stocks in global grasslands in the year 2010. It also summarises the assessment of the carbon input levels needed to maintain current SOC stocks, and the evaluation of the soil organic carbon sequestration potential of grasslands if management practices known to improve soil organic carbon sequestration are implemented worldwide

The results show the importance of the interaction between climate and grassland management, with the latter playing a crucial role in the quality and quantity of organic material entering the soil. The report provides spatially explicit evidence on the state of grassland soils and can be used as a baseline for future work to explore the impacts of livestock management on soil organic carbon at regional, country and farm levels.

Grasslands are one of the major ecosystems of the world, covering close to one-third of the Earth's terrestrial surface. Extensively managed grasslands are recognized globally for their high biodiversity, and together with other rangelands, they often contribute to agricultural production through livestock browsing on natural forage, leaves, soft shoots and shrubs. It is, therefore, evident that assessing the current state of grassland systems, and their potential to sequester carbon in the soil, is of key importance for understanding the trade-offs between grassland services on food security, biodiversity conservation and climate mitigation and offsets, and how current grassland management could be improved to meet global climate targets.

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