SOIL CARBON SEQUESTRATION BY SUSTAINABLE MANAGEMENT PRACTICES: POTENTIAL AND OPPORTUNITY FOR THE AMERICAS

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IICA
Living Soils of the Americas
ESALQ USP
The Ohio State University
C•MASC

Editorial coordination: Federico Villareal
Mechannical editing: Catalina Saraceno
Layout: Nadia Cassullo
Cover design: Nadia Cassullo
Printing: IICA Print Shop

Soil carbon sequestration through adopting sustainable management practices: potential and opportunity for the American countries / Carlos Eduardo Pellegrino Cerri… [et al.]. – San José, C.R.: IICA, 2021
60 p.; 21x16 cm.

ISBN: 978-92-9248-958-8

1. Carbon sequestration 2. Sustainable land management 2. soil management 4. Climate change mitigation 5. Carbon dioxide 6. Greenhouse gas emissions 7. Emission reduction 8. Cover plants 9. Americas I. Cerri, Carlos Eduardo Pellegrino II. Cherubin, Mauricio Roberto III. Damian, Junior Melo IV. Mello, Francisco Fujita de Castro V. Lal, Rattan VI. IICA VII. Title

AGRIS	DEWEY
P30	333.822

San Jose, Costa Rica
2021

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Preface

Manuel Otero
Director General
del Instituto Interamericano
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It is a great pleasure for the Inter-American Institute for Cooperation on Agriculture (IICA) to present one of the first products of the initiative Living Soils in the Americas (LiSAm) prepared by a group of renowned scientists and led by Prof. Rattan Lal. This document entitled "Soil carbon sequestration through adopting sustainable management practices: potential and opportunity for the countries in the Americas" is highly informative and provides an excellent synthesis of the state of the knowledge related to the carbon sequestration potential for soils in the Americas.

Living Soils in the Americas (LiSAm) offers a unique opportunity as it will draw on the scientific and technical backstopping of the Carbon Management and Sequestration Center at The Ohio State University (CMASC), as well as on IICA's network of 34 country representations that operate in close cooperation with the Ministries of Agriculture, in order to respond to the most pressing agricultural challenges in the hemisphere.

LiSAm is a timely international and multi-stakeholder initiative to fine-tune, apply and adapt methodologies and technologies to sequester soil organic C across a diversity of agricultural systems, thus embracing the holistic One Health approach. It aims to provide policymakers, farmers and other value chain actors with the tools to assess and increase the environmental services that agriculture can provide through improved soil management in support of the achievement of the UN Sustainable Development Goals (SDGs), Nationally Determined Contributions (NDCs) and the Land Degradation Neutrality (LDN) Target.

Therefore, as part of the LiSAm, the present document represents a great reference material that is divided into four main sections. The first section presents an up-to-date introduction about soil C sequestration to promote food security and mitigate climate changes. Section II presents a complete protocol for measuring soil C stocks and GHG emissions, including not only field conditions approaches but also large-scale assessment of soil C stock and greenhouse gas emissions using mathematical tools and simulation models. The third brings a series of informative maps and a few case studies on the potential soil C sequestration by adopting sustainable management practices. The final section addresses the main findings of the document, aimed at helping potential participants of the initiative to get informed about this hot topic, and may facilitate collaboration among agricultural stakeholders, scientists and donors to address the challenge of demonstrating that soil C sequestration in agricultural lands is one of a few strategies that could be applied on large scales and at potentially low cost, that could be beneficial to farmers and at the same time, contribute towards the goals set in the Paris Agreement. Faced with the information provided in this document, IICA believes that sustainable management practices suggested by the LiSAm initiative can guide new protocols for curbing land degradation, as well as promote soil health and soil C sequestration in the American continent.

Authors

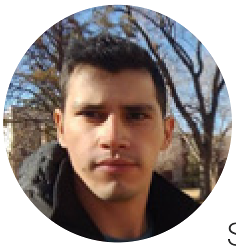
Carlos Eduardo Pellegrino Cerri

Is a professor at the “Luiz de Queiroz” College of Agriculture (ESALQ) at the University of São Paulo (USP), where he teaches courses to undergraduate and graduate students. He worked three years on an international project funded by the Global Environment Facility, which is a part of the United Nations Environment Programme. A significant portion of his studies were carried out in the Amazon region (including his PhD thesis and post- doctoral research related to land use changes in the Amazon). His main areas of research are related to soil organic matter dynamics in tropical regions, greenhouse gas emissions in agriculture, mathematical modeling applied to soil science, soil properties spatial variability and global climate change. He is an advisor to numerous national and international foundations and organizations, as well as national governments. He has published 1 edited book, 35 book chapters, and more than 200 scientific papers in peer-reviewed journals and edited volumes. Presently, he is the Coordinator of the Graduate Programme on Soil Science and Plant Nutrition, Vice President of the Graduate Program of ESALQ/USP, Vice Dean of the Soil Science Department, Member of the International Affairs Committee at ESALQ/USP, Member of the Scholarship Committee at ESALQ/USP and Member of the Advisory Commission at ESALQ/USP. He is an affiliated member of the Brazilian Academy of Science, Sociedade Brasileira de Ciência do Solo, International Humic Substances Society, Soil Science Society of America, American Society of Agronomy and Crop Science Society of America.

Mauricio Roberto Cherubin

Is a professor in the Department of Soil Science at the "Luiz de Queiroz" College of Agriculture, University of São Paulo (ESALQ/USP) in Piracicaba, São Paulo, Brazil. Prof. Cherubin is also an Agronomist trained at the Federal University of Santa Maria (UFSM), and holds a Bachelor of Administration from the Federal University of Santa Catarina, a Masters in Agronomy, Agriculture and Environment (UFSM) and a PhD in Soil Science and Plant Nutrition (ESALQ/USP). He spent one year as visiting researcher at the United States Department of Agriculture (USDA) - National Laboratory for Agriculture and the Environment (NLAE) in Ames, Iowa, USA, where his studies were focused on the development and application of multiple approaches and tools to evaluate soil health in tropical regions. Prof. Cherubin did his post-doctoral studies at the Environmental Biogeochemical Laboratory at the Center for Nuclear Energy in Agriculture (CENA/USP) in Brazil. Currently, he teaches courses and supervises undergraduate (Agronomy, Forestry and Environmental Management) and graduate students (Soil and Plant Nutrition). He also created and has led the Soil Health & Management Research Group – SOHMA at the ESALQ/USP. He has published 133 peer-reviewed scientific papers, and more than 170 abstracts for congresses and conferences. Moreover, he manages large research projects funded by public and private agencies, and has been active in scientific cooperation networks with researchers from prestigious national and international institutions focusing on topics related to land use and soil management, soil health, soil carbon sequestration, nature-based solutions and ecosystem services.

Junior Melo Damian

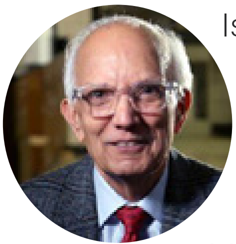


Possesses a PhD in Soils and Plant Nutrition from the "Luiz de Queiroz" College of Agriculture - University of São Paulo, 2017-2021), a Masters in Agronomy (Agronomy, Agriculture and Environment) from the Federal University of Santa Maria (2015-2017), is an Agronomist trained at the Federal University of Santa Maria (2010-2015) and an Agricultural Technician trained at the Cruzeiro do Sul Technical School (2006-2009). He has experience in planning, executing, analyzing, and writing scientific papers in the area of soil science. His main research focuses on evaluating and predicting (mathematical modeling) the soil carbon (C) dynamics with the change in land use in Brazil, mainly due to the adoption of sustainable production systems. Júnior has published 34 scientific papers in peer-reviewed journals, 5 book chapters, and 56 abstracts for scientific events. In addition, he is reviser for 15 important scientific journals.

Francisco Fujita de Castro Mello

Is Head of the Center for Knowledge and Horizontal Cooperation within the Directorate of Technical Cooperation of the Inter-American Institute for Cooperation on Agriculture (IICA). He is an Agronomist with a Masters in Agronomy (Soil Sciences) and PhD in Sciences from the University of Sao Paulo where he focused on soil carbon stocks dynamics and climate change. He has carried out studies to evaluate the impact of land use changes and greenhouse gas emissions in agricultural regions with the aim of producing food and bioenergy in tropical regions. He has participated as a visiting researcher at the prestigious Sustainability Sciences Program of the John F. Kennedy School of Government, Harvard University, where he was a Giorgio Ruffolo Fellow (2011-2012). He served important institutions in Brazil as a Climate Change specialist at the Brazilian Agriculture and Livestock Confederation (CNA) and was General Coordinator and Deputy Director of the Department for Production Systems and Sustainability at the Secretariat for Agricultural Development and Cooperatives of the Ministry of Agriculture, Livestock and Supply; Director of the Department of Production Promotion and Productive Structuring and Deputy Under Secretary of the National Secretariat for Food and Nutritional Security, a part of the Ministry of Social Development. He was also Counselor of the National Environmental Council (CONAMA) and focal point of the United Nations - 10YFP - Sustainable Food Systems Programme.

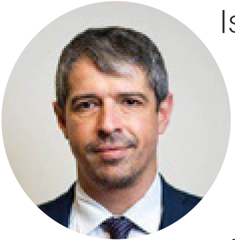
Rattan Lal



Is a Distinguished University Professor of Soil Science and Director of the CFAES Dr. Rattan Lal Carbon Management and Sequestration Center at The Ohio State University, as well as an Adjunct Professor of the University of Iceland and the Indian Agricultural Research Institute (IARI) in India. He received a B.S. from Punjab Agricultural University, Ludhiana, India (1963); M.Sc. from the Indian Agricultural Research Institute, New Delhi, India (1965); and a Ph.D. from the Ohio State University, Columbus, Ohio (1968). He served as Sr. Research Fellow with the University of Sydney, Australia (1968-69), Soil Physicist at IITA, Ibadan, Nigeria (1970-87), and Professor of Soil Science at OSU (1987 to date). He has authored/co-authored over 1000 refereed journal articles and more than 550 book chapters, has written and edited/co-edited more than 100 books. He was included in the Thomson Reuters list of the World's Most Influential Scientific Minds (2014-2016), and he is among Clarivate's Highly Cited Researchers in Agriculture (2014-2020), as well as ranked #111 globally and #1 in Agriculture and Agronomy among the top 2% of scientists by Ioannidis et al. (2019, 2020). He has received an Honoris Causa degree from nine universities throughout Europe, USA and Asia; the Medal of Honor from

UIMP, Santander, Spain (2018); the Distinguished Service Medal of IUSS (2018); and is fellow of five professional societies. Dr. Lal has mentored 112 graduate students and 181 visiting scholars from around the world. He was President of the World Association of Soil and Water Conservation (1987-1990), International Soil and Tillage Research Organization (1988-1991), Soil Science Society of America (2006-2008), and the International Union of Soil Sciences (2017-2018). He holds the Chair in Soil Science and Goodwill Ambassador for Sustainability Issues for the Inter-American Institute for Cooperation on Agriculture (IICA), and member of the 2021 United Nations Food Security Summit Science Committee and Action Track 3. Dr. Lal is a laureate of the GCHERA World Agriculture Prize (2018), Glinka World Soil Prize (2018), Japan Prize (2019), U.S. Awasthi IFFCO Prize (2019), Arrell Global Food Innovation Award (2020), World Food Prize (2020), and Padma Shri Award (2021).

Coordinator: Federico Villareal



Is Director of Technical Cooperation at IICA. He holds a PhD in Geography from the University of Buenos Aires (UBA), a Master's Degree in Agrarian Social Studies from the Latin American Faculty of Social Sciences (FLACSO), a Degree in Economics and Agricultural Administration from the Faculty of Agronomy at the University of Buenos Aires (FAUBA) and a Bachelor of General Agronomy from the Don Bosco Salesian Agrotechnical School in Uribelarrea, Argentina. He has been a career researcher at the National Council for Scientific and Technical Research (CONICET) in the Regional and Territorial Studies Program (PERT) of the Institute of Geography (FFyL-UBA) and professor of Theory and Economic Policy and Spatial Analysis in the field of Geography. He has extensive experience as a director and researcher trained in research projects on various topics related to development and rurality, among which the following stand out: bioeconomy, seed market, biotechnology, neo-rurality, public policy, family farming, changes in land use, rural development, territory, security and food sovereignty, among others. These projects have been financed by diverse and recognized national and international sources. He has carried out various national and international consultancies at the Ministry of Agroindustry and the Ministry of Science, Technology and Productive Innovation of Argentina, and the Food and Agriculture Organization of the United Nations (FAO). He is a professor of the Master's Degree in Rural Development at FAUBA and the Master's Degree in Social Studies at FLACSO / Argentina, among other higher education institutions. He is the author of more than 50 publications including books, magazine articles and presentations at multiple conferences.

Executive summary

Soils represent an important carbon (C) pool, being the large sink among the terrestrial ecosystem compartments. However, intensive use of the soils to meet the growing demand for food, fiber and energy has caused soil C losses and consequently, the emissions of greenhouse gases (GHG). For this reason, sustainable soil C sequestration practices and well-oriented political agendas need to be scaled up to regional and national levels to contribute to climate change mitigation and food security. In 2020, the Inter-American Institute for Cooperation on Agriculture (IICA) and the Carbon Management and Sequestration Center at The Ohio State University (CMASC) launched the Living Soils of the Americas (LiSAm) initiative. The LiSAm is an extensive network involving governments, international organizations, universities, the private sector and civil society organizations that will join efforts to curb land degradation and thereby promote soil health, C sequestration and other associated benefits to people. In seeking to provide first data-tools for the LiSAm initiative in the American hemisphere, we prepared the present document with the main methodologies used for measuring soil C stocks and GHG emissions in the field, current land use and soil C stocks, and potential soil C sequestration by adopting sustainable management practices. As a result, we found that pasture is the most widespread agricultural use of land in the Americas, accounting for 9.05km^2 x 10^6 (905 million ha). Pasture surface area is three times larger than that of agriculture (croplands), accounting for 3.40 km^2 x 10^6. Soybean (0.91 km^2 x 10^6), maize (0.72 km^2 x 10^6) and wheat (0.35 km^2 x 10^6) are the most cultivated annual crops, sugarcane (0.14 km^2 x 10^6) is the main semi-perennial crop, and coffee (0.05 km^2 x 10^6) is the main perennial crop. For the soil C stocks, we estimated an average accumulation of 51.28 Mg ha-1 in the entire hemisphere for the 0-30 cm layer. Among the different regions, Central America (63.30 Mg ha^{-1}), the Caribbean (61.35 Mg ha^{-1}) and North America (53.91 Mg ha-1) showed the highest soil C stocks; only in South America the soil C stock (48.11 Mg ha^{-1}) was below the mean established for the entire continent. Several approaches to assessing soil C sequestration and GHG emissions were presented and discussed, ranging from site-specific field measurements to mathematical tools and simulation models. Lastly, we identified some promising sustainable management practices that could be adopted across the Americas, such as no-tillage, cover crops, organic amendments, pasture restoration through integrated systems (i.e., silvopastoral and integrated crop-livestock-forest systems), forest restoration, among others. Based on our estimate, adopting only two large-scale sustainable management practices (i.e., pasture reclamation and conservation tillage) the potential soil C accumulation in the countries of the Americas is about 2.68 Pg C (1.25 – 4.11 Pg C), representing a total of 9.81 Pg

CO_2eq. (4.56 – 15.06 Pg CO_2eq) over 20 years. It represents a potential to mitigate about 7.9% (3.7 – 12.2%) of the total annual global net anthropogenic GHG emissions due to agriculture and 4.1% (1.9 - 6.3%) of global emissions due to agriculture, forestry, and other land use. Faced with the information provided in this document, we believe that sustainable management practices suggested by the LiSAm initiative can guide new protocols for curbing land degradation, promote soil health and soil C sequestration in the Americas.

1

Soil C sequestration to promote food security and mitigate climate change

Global population is expected to reach 9.7 billion people in 2050 (United Nations 2019). Population growth pressures the natural resources to meet the increasing demands for basic-human needs, such as food, fiber, fresh water and energy. In response to the intensive anthropic activities, the emissions of greenhouse gases (GHG) to the atmosphere have experienced unprecedented growth since the period of the pre-industrial revolution (IPCC 2021). As a consequence of the increase in GHG emissions, the average temperature of the Earth rose by 1.1 ºC when compared to pre-industrial periods, with an even higher increase (1.6 °C) in the continents. Therefore, human-induced global warming has impacted climate conditions across the globe (IPCC 2021). Climate changes have increased the frequency of extreme weather, which threatens food production and human well-being in the coming decades.

In light of this current scenario, ensuring food security and mitigating global warming are among the major challenges for humankind in the XXI century. Bearing in mind the importance of joint action by all countries in the world to mitigate GHG emissions and the negative consequences of climate change, the Paris Agreement was signed by most of the countries with the aim of ensuring that global warming remains below 2°C by 2050, with efforts to limit it to 1.5 °C (Rogelj *et al.* 2016).

Several climate change mitigation pathways have been proposed as cost-effective options to decarbonize the atmosphere, including C capture, utilization and storage technologies (CCUS) (e.g., Wei *et al.* 2021), bioenergy with C capture and store technologies (BECCS) (e.g., Hanssen *et al.* 2020), and nature-based solutions (e.g., Girardin *et al.* 2021, Seddon *et al.* 2021), also called natural climate solution (Griscom *et al.* 2017). The most promising nature-based solutions are associated with native forest restoration, grassland/pastureland reclamation, and adoption of climate-smart agricultural management practices (Girardin *et al.* 2021, Horton *et al.* 2021). Nature-based solutions can deliver many local ecological and socio-economic benefits (Girardin *et al.* 2021), through the removal of CO2 from the atmosphere by photosynthesis performed by plants, and storing C in the living biomass of plants and animals, or in the soil. Currently, land (soil and vegetation) absorbs about one-third of all anthropogenic emissions (Friedlingstein et al. 2020).

Global soil organic C stocks are estimated to range from 1,500–2,400 Pg (~5,500–8,800 Pg CO_2) in the 0-1 m depth (Lal 2018, Smith *et al.* 2020, Lal et al. 2021). Soil represents the largest terrestrial pool of C (***Figure 1***), being equivalent to approximately three times the C stocks in vegetation, and twice the stock of C in the atmosphere (Smith et al. 2020, Lal *et al.* 2021). Therefore, small changes in C stocks can therefore have significant impacts on the atmosphere and climate change. Recent estimates show that soil C represents 25% of the potential of nature-based solutions (total potential, 23.8 Pg of CO_2-equivalent per year), of which 40% is protection of existing soil C and 60% is rebuilding depleted stocks (Bossio *et al.* 2020). Historically, cultivated soils lost around 115–154 Pg C to the atmosphere (Sanderman *et al.* 2017, Lal 2018), and therefore, restoring soil C stocks can offset those emissions.

FIGURE 1

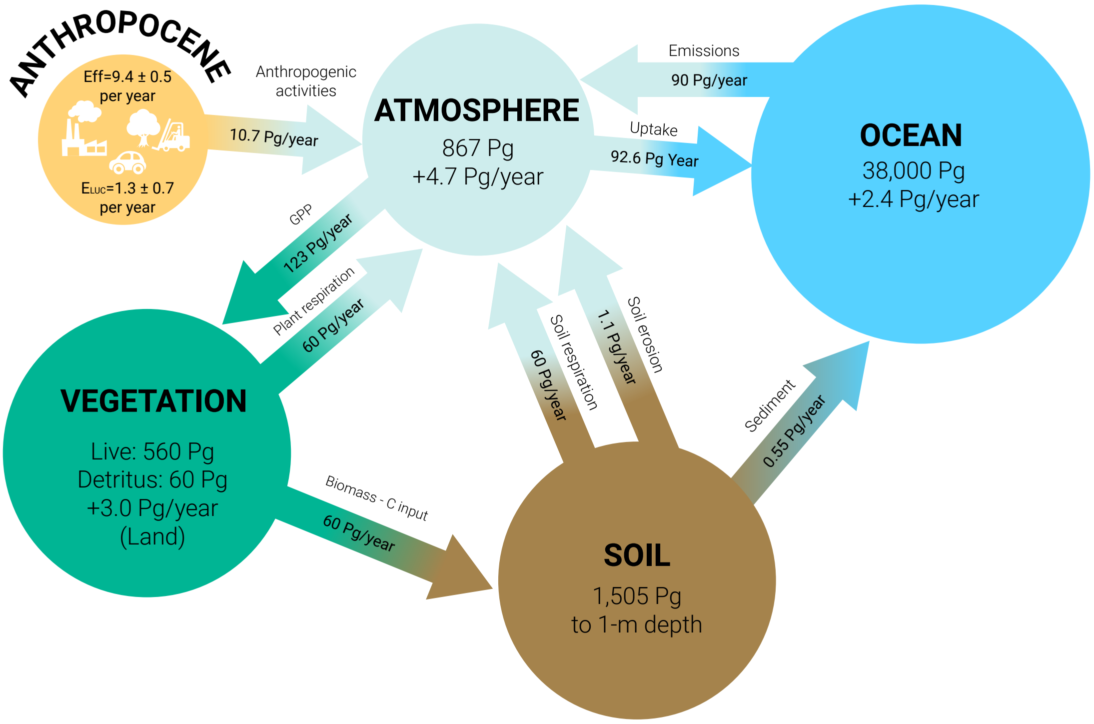


Figure 1. The contemporary global C cycle. Data within arrows indicate fluxes (Pg C/year), those within circles indicate the magnitude of stock, and the data in circles with + sign indicate the annual rate of change of the stock. Within the circle-labeled Anthropocene, EFF is emissions by fossil fuel and ELUC is the emissions by land use conversion. Atmospheric stock is computed on the basis of 406.29 ppmv of CO_2 on 26 November 2017 (0.040629% by volume) and 0.06122% by mass of atmosphere is 5.148 x 1,021 g, containing 3,177 Pg CO_2 or 867 Pg C. References for the data used to build this figure can be found in Lal (2018).
Source: Lal (2018).

Although soil can act as a source of CO_2 and other GHG, if well-managed it can become a large sink of atmospheric CO_2. Introducing judicious land use and science-based management practices can prevent C emissions and remove atmospheric CO2 (Paustian *et al.* 2016), thus making the soil a negative emission technique (Smith 2016). Healthy and re-carbonized soils contribute to delivering food and climate security (Lal 2004, Horton *et al.* 2021, Lal *et al.* 2021), as well as other essential ecosystem services, such as biodiversity and water quality (Smith *et al.* 2021).

Nevertheless, to promote soil C sequestration is a complex task and takes time (Smith *et al.* 2021). To achieve soil sequestration, sustainable management practices must address the two “gold” principles: i) to provide abundant and continuous C inputs into the soil to increase C stocks (i.e., increase C inputs); and ii) to reduce GHG emissions from the soil (i.e., reduce C losses). In nature, not all the CO2 removed from the atmosphere by plants is, in fact, stored in plant biomass or in the soil for a long time. When a plant dies or is harvested, most of the C (60-90%) incorporated as organic components into its above- and belowground biomass returns to the atmosphere as CO_2 during the soil biota-mediated decomposition process. The C that remains in the soil is incorporated and stabilized into the different soil organic matter pools (***Figure 2***), such as particulate and mineral-associated organic matter, which have distinct composition, persistence time and functionality in the soil and environment (Lavallee *et al.* 2020).

FIGURE 2

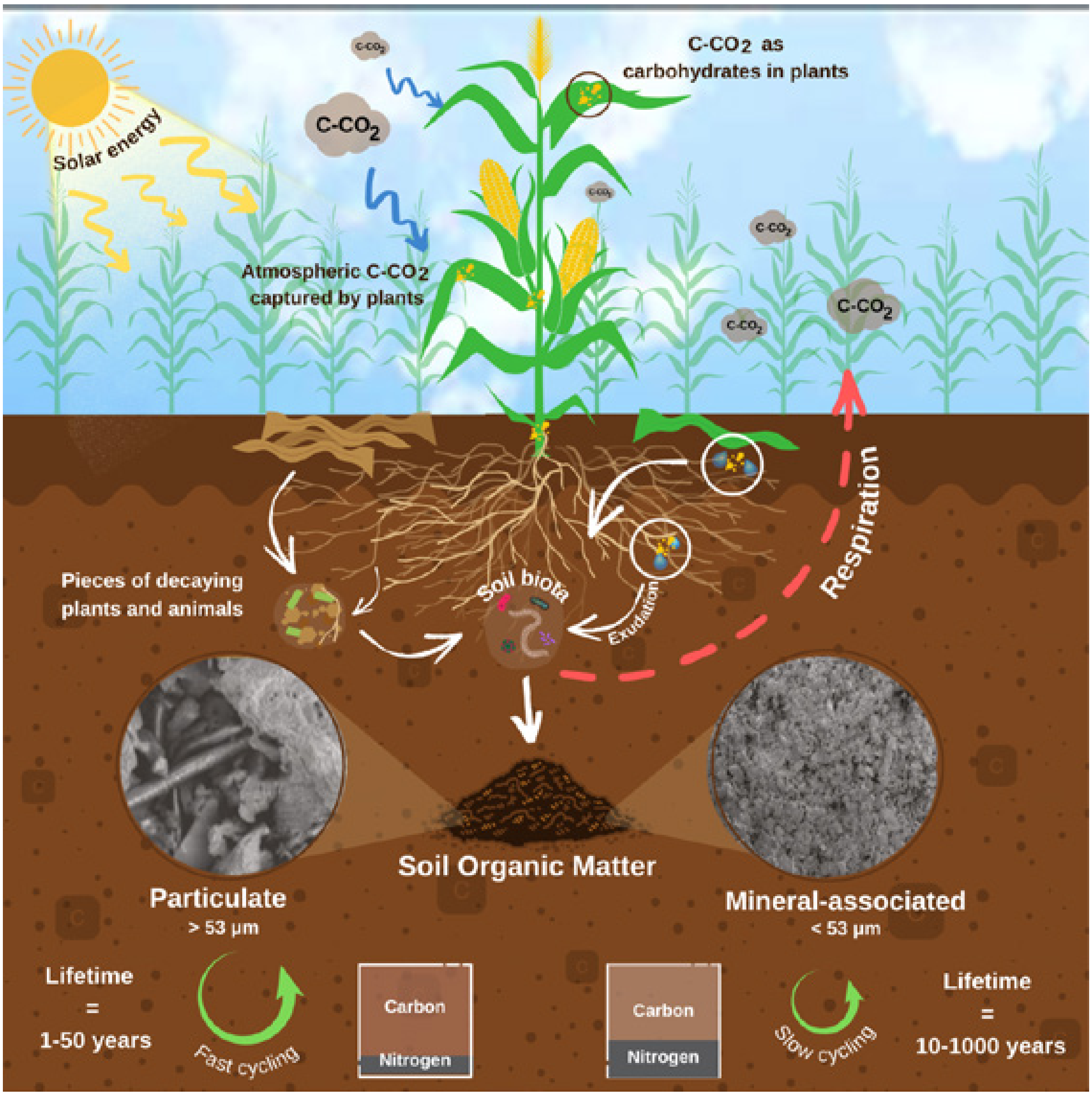


Figure 2 -How C cycles into and out of soil, highlighting the soil C storage in different soil organic matter pools (particulate and associated to minerals).
Source: redesigned from Jocelyn Lavallee.

Particulate organic matter fraction can be infinitely accumulated in the soil, but it is mineralized faster (short residence time in the soil) thus contributing to nutrient cycling and to sustaining biological activity. In contrast, mineral-associated organic matter fraction is subject to saturation, but has higher stability and persistence in the soil and therefore, is key to soil structure and to sequestering C for a longer time. To sustain healthy soils, both fractions are important, each one performing its specific functions (Hoffland *et al.* 2020).

The fluxes, stocks and transformation of the C in the soil-plant-atmosphere continuum are regulated by local to regional drivers, such as inherent soil characteristics, quantity and quality (biochemical composition) of plant-derived C inputs, weather conditions, and soil management choices (Lal 2018, Wiesmeier *et al.* 2019). Overall, tropical climate conditions, as observed in the major part of the Latin American territory, favor soil microbial respiration, leading to higher C losses to the atmosphere than temperate climate conditions (as observed in the major part of North America). On the other hand, if well-managed, tropical ecosystems can support higher biomass growth (i.e., higher CO_2 removal) and consequently, higher amounts of Care added to the soils.

In fact, regardless of the location, the Americas region has great potential for contributing to climate change mitigation and establishing strategies for adaptation. An extensive body of research has shown multiple options for sustainable management practices that could be adopted in the different agro-ecological regions of the hemisphere to sequester C, and contribute to climate regulation, food production and other environmental benefits, considering the social preferences and economical contexts. Examples of practical and feasible agricultural management practices include conservation tillage, grazing management, organic amendments (manures, agro-industrial residues and biochar), cover cropping, mulching, fertility management, integrated agricultural systems (agroforestry, silvopastoral, crop-livestock-forest systems), and water management, among others (Smith *et al.* 2008, Paustian et al. 2016, Lal *et al.* 2021). Recent estimates revealed that only croplands in the Americas can promote soil C stock gains from 0.24 to 0.50 Pg y^{-1} in a time span of 20 years (Zommer *et al.* 2017).

However, to achieve this potential of soil C sequestration, it is necessary to establish well-oriented national and international technical and political agendas for promoting and subsidizing the implementation of practical and applicable actions on soil health and C sequestration. In addition, guidelines for monitoring, verification and reporting the results are fundamental to evaluate the effectiveness of such actions. In this context, a continental initiative, called the “Living Soils of the Americas (LiSAm)”, led by the Inter-American Institute for Cooperation on Agriculture (IICA)[1] and the Carbon Management and Sequestration Center at The Ohio State University (CMASC) was launched on 5 December 2020 on World Soil Day. The LiSAm is an extensive network involving governments, international organizations, universities, the private sector and civil society organizations that will join efforts to curb land degradation, and consequently, to promote soil health, C sequestration and other associated benefits to mankind.

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[1] https://www.iica.int/es

In the following sections of this document, the main methodologies used for measuring soil C stocks and GHG emissions in the field, current land use and soil C stocks, and potential soil C sequestration through the adoption of sustainable management practices in the hemisphere will be presented and discussed.

Measuring soil C stocks and GHG emissions

Field measurements of soil C stocks

Soil C stock changes induced by land use changes and/or management practices can be assessed using two main approaches, diachronic and synchronic. In the diachronic approach, it is necessary to conduct field experiments in which soil C stocks are measured over time on the same experimental plots with different land-use or management treatments. This approach provides good accuracy and repeatability of measurements, but it is costly and often has a time limit. On the other hand, in the synchronic or chronosequence approach, samples are taken at the same time from field plots under different land-use or management systems at known durations from an initial reference state, and the soil C stocks are compared to those from soils under this initial reference state. This approach is based on the assumption that space substitutes time, in which the initial soil conditions of an area under the different land-use or management systems are very similar and in fact, that all factors (soil type, climate, relief, etc.) other than land-use or management are not influencing the results. Therefore, the accuracy and reliability of data collected using the synchronic approach depends on a judicious selection process of the study sites, which should be truly comparable. To learn more about synchronic and diachronic approaches to assess soil C stock changes, we recommend consulting Costa Junior *et al.* (2013).

Once the assessment approach is defined, direct measurements of soil C stocks rely on appropriate soil sampling methodology, which should be compatible with the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019b), as well as the ISO standards related to soil quality sampling (e.g., ISO 18400-101: 2017; ISO 18400-102: 2017; ISO 18400-104: 2018; ISO 18400-205: 2018). Other valuable information related to soil sampling for soil C measurement are available in Cerri *et al.* (2013), Wills *et al.* (2018), FAO (2020) and Smith *et al.* (2020).

Soil sampling design

Soil sampling for direct measurements has to deal with the natural and human-induced spatial variability of soil C stocks in the area. Therefore, soil sampling points should be as representative as possible of the entire area being characterized. Pre-selection of the area where samples will be taken could be made using soil maps, land use maps, aerial photographs, satellite images, and land use history. In parallel to the office work, site visits can be used to establish the location of the sampling points.

In the field, the simple random sampling scheme is widely used to represent a given land use or management practice, particularly when the synchronic approach (i.e., chronosequences or paired areas) is used to assess soil C changes. This is the simplest way to select independent and unbiased samples, which sample locations each have an equally probable chance of being selected (Wills *et al.* 2018). At each sampling point, we recommend establishing a 3×3 grid, with each point 50m apart from the other, totaling nine points that cover an area of one hectare (Figure 3).

In addition to defining a suitable number of sampling points, the sampling depth is a crucial factor for properly evaluating changes in soil C stocks (Smith *et al.* 2020). The IPCC (IPCC 2006) recommends considering at least the top 0.3m of the profile and adapting according to specific situations. The first 30 centimeters of the soil profile is the layer most affected most affected by land use and management practices, being the principal zone for root growth and biological activity. Therefore, the greatest soil C chances are expected to occur in this surface layer. However, the adoption of deep-root cash and cover crops into cropping rotation plans, and the introduction of trees as a component of integrated agricultural systems (e.g., agroforestry, silvopastoral and crop-livestock-forest systems) are some of the reasons that deeper soil sampling (down to 1 m or more), have been recommended to proper evaluation of the soil C changes over time (Cerri et al. 2013, FAO 2020, Smith *et al.* 2020). Based on that, samples could be taken from the following soil layers: 0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.6, 0.6-0.8 and 0.8-1.0 m for three out of nine trenches and 0-0.1, 0.1-0.2, 0.2-0.3 m in the other six trenches (***Figure 3***). In the 1-m deep trenches, it is recommended that two or three samples be collected in each layer down 30 cm, to increase the number of samples and consequently, the accuracy of soil C content and bulk density data. In summary, in each study area a total of 63 disturbed samples will be collected for soil C content quantification (9 points x 7 layers), and the same number (63) of undisturbed samples for bulk density determination.

FIGURE 3

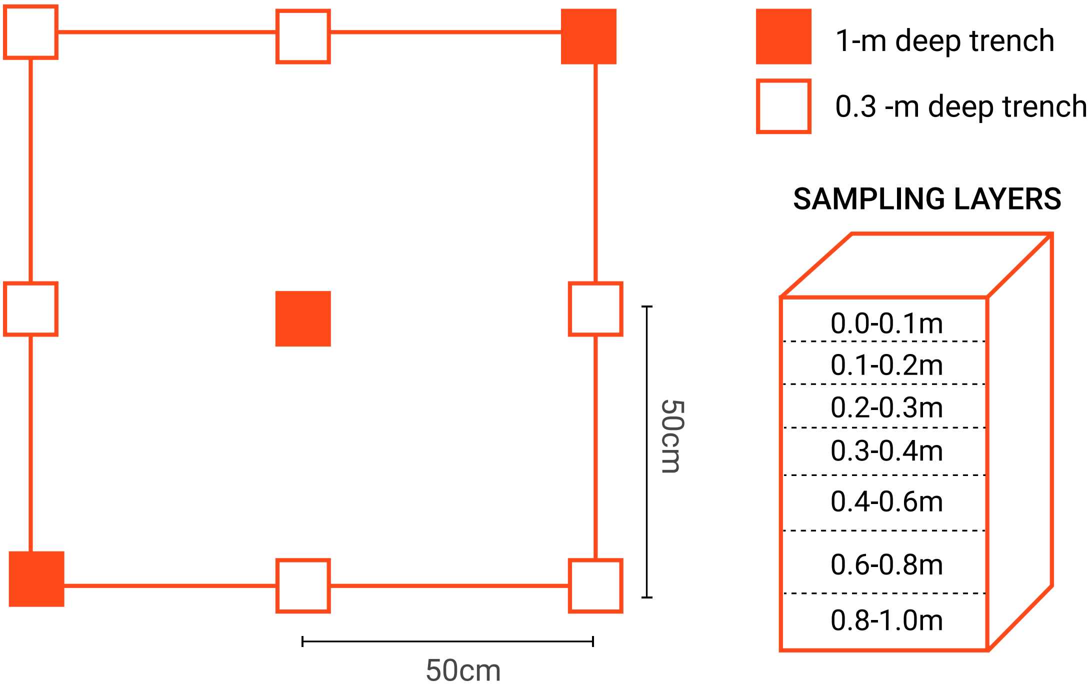

Figure 3. Soil sampling design for soil C and bulk density determinations, parameters used for soil C stock calculations. Nine trenches cover an area of a hectare, of which six trenches are used to take samples from the layer 0-0.1, 0.1-0.2 and 0.2-0.3 m layers, and in the remaining three trenches, soil is sampled from 0-0.1, 0.1-0.2, 0.2-0.3, 0.3-0.4, 0.4-0.6, 0.6-0.8 and 0.8-1.0 m layers.

It is worth mentioning that this soil sampling protocol can be adapted according to site-specific conditions. For example, when experimental plots (diachronic approach) are sampled, the number of points and the distance between them will likely need to be reduced, due to the limited size of the plots. In these cases, samples can be collected in the tree central trenches (two 0.3-m deep and one 1-m deep), for example. The reduced number of samples collected in each plot is compensated by the number of field repetitions (blocks) and the strict local control of the experiments. Moreover, in long-term experiments, sometimes soil samples are collected using augers or specific probes instead of trenches to avoid repeated soil disturbance in the plots over time.

Sampling procedures

The first step of soil sampling is removing the vegetation or plant litter from the soil surface. Carefully, the fine litter closer to the soil surface must be dusted off, avoiding the removal of soil particles from the surface layer. After that, the trenches are dug down to the desired depth of sampling. This process can be manual or using mini excavators, particularly for deeper trenches. The deeper trenches will measure 1.5 (depth) × 1.5 (length) × 1.0 (width) m, and the smaller trenches will measure 0.4 × 0.4 × 0.4 m. A critical aspect during the trench opening is to preserve at least two walls of the trench, preventing disturbances on soil structure where samples will be taken.

In the trench wall, soil samples are collected layer by layer from the top to the bottom using spatula or similar tools. In addition, next to the areas where samples were collected for C quantification, undisturbed samples (i.e., with preserved structure) have to be collected using a metal cylinder (~100 cm^3) to determine soil bulk density. Soil samples should be conditioned in plastic bags previously labeled and taken to the laboratory for preparation and analysis.

Carbon content and bulk density determination

Samples will be air dried, homogenized and sieved in a 2 mm screen. The fraction greater than 2 mm needs to be weighed to calculate the adequate C stock for the given soil layer, although this fraction is considered as C free. Subsamples (10 g) of the soil sieved in 2 mm screens should be ground and sieved at 0.150 mm (100 meshes) for C determination by dry combustion (Nelson and Sommers 1996). Total C should be determined by dry combustion using an elemental analyzer (furnace at 1,100-1,500 °C with pure oxygen). This method provides total C, which is composed of inorganic (from carbonates) and organic C. In most tropical soils, the inorganic C content is small; therefore, the total C content determined by dry combustion is mostly organic fraction. However, in soils with high carbonate content, the organic C determination can be done by wet oxidation with dichromate (Walkley and Black 1934) or by dry combustion after a preliminary removal of carbonates with acid, typically HCl 0.1M (Schumacher 2002).

Undisturbed samples are oven-dried at 105 °C for 48 h and weighed. Then, bulk density (Mg m^{-3}) can be calculated by dividing the soil dry mass by volume of the cylinder (Dane and Topp 2002).

Calculation of soil C stock and soil C change rate

Soil C stocks are calculated for all soil layers, according to Equation 1:

$$\text{Soil C stock} = \text{C} \times \text{bulk density} \times \text{soil layer} \qquad \textbf{(Eq. 1)}$$

where, C stock is expressed in Mg ha-1, C is the element content in %; bulk density is expressed in Mg m-3; and the soil layer is the thickness of the sampled layer in cm.

Since soil C stock is also a function of bulk density, factors such as machinery traffic, animal trampling and soil tillage affect soil bulk density and influence the results by under- or overestimating the real changes in the soil C stocks induced by land use and management practices. Therefore, the most widely accepted methodology to correct soil C stocks is based on the equivalent mass approach (Ellert and Bettany 1996). Carbon stocks in the areas being evaluated should be calculated on an equivalent depth basis, i.e., considering the depth that contains the same mass of soil as the corresponding layer of the reference area. In general, the previous land use (e.g., pasture or annual crop site) or a native vegetation site is considered the reference, depending on the land use history of the evaluated area.

The soil C stock change rate (Mg ha^{-1} y^{-1}) induced by land use or management practice adopted over time can be calculated according to Equation 2.

$$\text{Soil C stock change rate} = \frac{Soil\ C\ stock_{final} - Soil\ C\ stock_{initial}}{years} \qquad \textbf{(Eq. 2)}$$

where, Soil C stock change rate is the annual rate of C loss or accumulation (Mg ha^{-1} year^{-1}) in a given management scenario; Soil C stock$_{final}$ is the current soil C stock (Mg ha-^{1}) after a given time of management adoption; Soil C stock$_{initial}$ is the referential C stock (Mg ha^{-1}) in the past (baseline); and years is the period over which such management has been adopted.

Field measurement of greenhouse gas (GHG) emissions

Greenhouse gases (CO_2, CH_4 and N_2O) are continually being emitted from the soil to the atmosphere. However, the quantification of these gases and the extrapolation of the results for a given area or period is still challenging because of their low concentration and the spatio-temporal variability of the emissions in the environment. Despite that, there are several methods for GHG sampling in the field, from simpler and widely used enclosure methods (static and dynamic chambers), to more complex and expensive micrometeorological methods (e.g., tower of eddy covariance) (***Figure 4***).

FIGURE 4

Figure 4. Methodologies used for sampling greenhouse gases emitted from the soil in the field. a) static chambers; b) dynamic chambers, c) tower of eddy covariance.
Photos: Carlos E.P. Cerri

Static chambers are the most widely used method, because it is cheaper and simpler to be used. However, a static chamber covers a small soil surface area and many chambers are required for a representative emissions estimate. Also, the air sampling is manual and time consuming. On the other hand, more complex methods have the advantage of providing continuous and automatic measurement and achieving spatial integration of fluxes, but they are expensive, difficult to maintain in the field and require more expertise to deal with the data.

Since widely static chambers are still the most used methodology, we will detail GHG sampling in the field using this type of methodology, based on Cerri *et al.* (2013). Also, regardless of the methods used, the protocol should be in agreement with the recommended 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019b).

GHG sampling using static chambers

The static chamber system is composed of two parts, the base and the chamber. It is recommended that the chambers have a suitable thermal insulation and are made of material that does not result in an increase in the internal temperature. Chamber height affects the quality of chamber measurement in several ways. For better scaling of the size of the chamber, it is necessary to evaluate the incubation time. Large chambers and short incubation time result in underestimated GHG flux, while small chambers and long incubation time overestimate the results. For example, in sugarcane fields, Cerri *et al.* (2013) recommended a rectangular chamber with 0.70 × 0.45 m, in which the dimensions are associated with the traditional inter-row spacing (1.5 m). The use of fans inside the chamber is recommended in order to homogenize the air, especially in large chambers.

In the field, the base should be inserted into the soil one day before the beginning of gas sampling. Inserting the base at 0.05-0.10 m of soil depth is recommended. Introducing the base at a depth of less than 0.05 m can result in gas exchange between the inside and outside of the chamber, while deeper than 0.1 m may modify the water movement in the soil inside the chamber and consequently affect GHG fluxes.

The gas samples should be taken in the shortest time possible to observe a measurable increase in GHG headspace concentration. Initial headspace gas samples will be collected using 20-ml nylon syringes at the beginning of the incubation and, as guidance, at 15, 30 and 45 minutes thereafter. This is a general recommendation, but variation in this period of evaluation may occur depending on the GHG analyzed. The samples collected will be transferred to sealed pre-evacuated vials. In GHG sampling and storage, it is recommended that pressurized containers be used (vials, exetainers and vacutainers). Is not advisable to store gas samples using syringes (plastic or glass syringes). During the sampling period, collecting samples of standard gas (average concentration known) is advisable in order to analyze the reliability of the GHG storage system. To analyze the gas fluxes, samples inside the vials should be injected into the gas chromatograph.

The headspace temperature during gas sampling in the field is rarely the same as laboratory temperature at the time of air sample analysis. Thus, the temperature based on the perfect gas law should be corrected. Atmospheric pressure, soil temperature and soil moisture measurements should be performed during the gas sampling. Samples should be stored in vials and the maximum duration of sample storage would be 30 days.

The time of gas sampling depends on the situation evaluated. For example, for long term monitoring of land use change, it is recommended that samples be collected over the year every 15 or 30 days, encompassing the seasonality of GHG emissions that occurs in the rainy and dry seasons. On the other hand, when specific management practices are evaluated, such as mineral fertilization, the sampling period could be daily for the first 15 days, and then every three days for the next 15 days. For organic fertilizers/composts the sampling period should be longer than for mineral fertilizer, collecting daily for the first 15 days and then every three days for the next 75 days, totaling 90 days. For soil tillage, the pick of the GHG emission occurs in the first days after management; therefore, it is recommended that daily sampling be performed daily for the first 15 days, and thereafter, the frequency of sampling can be longer - every three days for next the 15 days and every seven days for the next 30 or 45 days.

GHG analyses and results

Gas chromatograph can be used to analyze GHG concentrations: Electron Capture Detector (63Ni) operated at 230o C to determine concentrations of CO_2 and N_2O and Flame Ionization Detector (FID) to quantify the CH_4 concentration in the same sample. Certified gases are used as standards, then fluxes are calculated based on the linear change in the gas concentration collected from the chamber during the incubation period. As an alternative to the static chambers, where possible, the eddy covariance technique can be used to measure fluxes on a quasi-continuous basis. The principle of this micrometeorological approach is that the exchange rate of a trace gas (flux) across the interface of the atmosphere and a plant canopy can be calculated as the covariance between fluctuations of vertical wind velocity and this gas (Baldocchi 2003).

The GHG fluxes are calculated from the increment in concentration during the incubation period when the chamber is attached to the base and expressed as arithmetic means with standard deviation. Cumulative fluxes are calculated by plotting daily fluxes over time, interpolating linearly between them and integrating the area under the curve.

Large-scale assessment of soil C stock and greenhouse gas emissions

Considering the various factors that directly influence soil C sequestration and GHG emissions, such as: soil type (mainly relative to mineral fraction), vegetation type (aerial part contribution and root system), climate (dry/cold versus wet/hot), relief (topography may favor, for example, accumulation of C in lowland regions), organisms (quantity and functional diversity), management practices (conservation practices such as well-managed pasture, no-tillage system and integration crop-livestock-forests tend to increase soil C, while degraded pastures, excessive use of plowing/harrowing tend to reduce soil C), its adequate assessment is a complex activity with varying uncertainty associated with the results obtained. In this context, several approaches have been proposed in an attempt to assess changes in soil C stocks, emissions of GHG mainly due to changes in land use and / or the adoption of management practices.

Among the main existing approaches (***Figure 5***) for estimating the variation of C stocks and GHG emissions, using tools or spreadsheets, one can mention the system proposed by the "Carbon Benefits Project" (CBP), the "EX-ACT" tool proposed by FAO. In addition, there are the calculation methods based on the Tier 1, Tier 2 and Tier 3 of the IPCC. These approaches are useful for obtaining general information, but they do not replace a more specific assessment based on field sampling and determination of soil C levels using an elementary analyzer (dry combustion method).

FIGURE 5

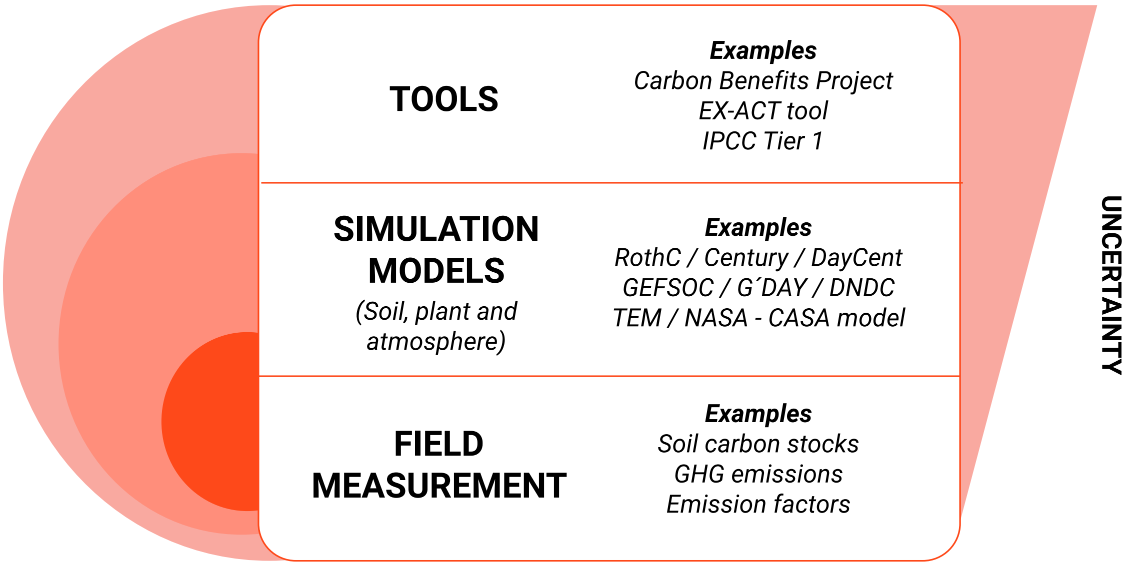

Figure 5. Approaches for assessing soil C and greenhouse emissions from the field (lower uncertainty) to regional/national scales (higher uncertainty).

The Carbon Benefits Project (CBP) provides tools for projects aimed at agriculture and forestry to estimate the impact of its activities in mitigating climate change, covering both changes in C stocks and greenhouse gas emissions. The tools can be used at all stages of a project, they are free and relatively easy to use. The tools are divided into a "simple" and a "detailed" module and were developed by Colorado State University and partners as part of a project co-financed by the Global Environment Facility (GEF) led by the UNDP United Nations Environment Program. The simplified module uses standard values ("default") extracted from the literature to estimate C stocks and gas emissions. In the detailed module, the user needs to insert more specific information about changes in land use and/or agricultural management practices such as the amount of fertilizer applied, types of crops, ways of preparing the soil, etc. Both CBP modules generate, as a result, general information about the situation assessed and provide the respective uncertainties associated with the estimates. Such tools are useful for the general assessment of projects that directly or indirectly aim to assess, roughly, the impacts of their activities on C stocks and gas emissions. CBP itself suggests that more accurate and monitoring-based assessments should be carried out with data directly obtained under field conditions and measured more specifically for each situation assessed (https://banr.nrel.colostate.edu/CBP/).

The EX-ACT tool (Ex-Ante Carbon-balance Tool) was developed by FAO in order to provide ex-ante estimates of the impact of agricultural and forestry development projects on greenhouse gas emissions and C sequestration, showing its C balance effects. For this purpose, the tool uses the standard values extracted from the IPCC reports (Tier 1) and/or more specific coefficients obtained from the literature for some situations associated with agroforestry systems (Tier 2). The user has access to a set of interconnected Excel spreadsheets to estimate the potential accumulations or losses of soil C and the emission of GHG. There is information that allows us to know the uncertainties associated with such estimates. Similar to the CBP tools, the EX-ACT was not designed to provide detailed or even specific information for a given situation. These are useful tools for general knowledge of the magnitude of the values of C stocks and GHG emissions from activities associated with agriculture and forestry systems (http://www.fao.org/tc/exact/ex-act-inicio/en/).

The Intergovernmental Panel on Climate Change (IPCC) classified the methodological approaches for national estimation of GHG emissions and C stocks into three different tiers (levels), according to the amount of information needed and the degree of analytical complexity. Tier 1 uses the standard emission factors ("default") provided by the IPCC, which is of general scope. In this sense, according to the IPCC, the stock change assessment method is not applicable in the context of Tier 1 due to the more specific data requirements of the situation to be assessed. Tier 2 is based on the same methodological approach as Tier 1, but uses emission factors and other country-specific parameters. Country-specific emission factors and parameters are most appropriate for that country's forests, climatic regions and land use systems. More highly stratified activity data may be needed for the Tier 2 approach to match country-specific emission factors and parameters for specific regions and specialized categories of land use. In Tier 3, simulation models are used, which must be adapted to meet national circumstances. If properly implemented, the simulation models can be combined with geographic information systems to cover greater territorial extensions. Progress from Tier 1 to Tier 3 may represent a potential reduction in the uncertainty in estimates of GHG emissions and variation in C stocks, but the reduced uncertainties associated with the procedure that calls for the collection of samples in the field, analysis in specialized laboratories and calculation of C stocks will be discussed further.

In addition to the above-mentioned tools, a variety of *process-oriented models* have been applied for simulations of soil C sequestration and GHG emissions. In the following section, a number of models are described in terms of their overall design and intended applications. To one degree or another, all of the models reviewed here attempt to compute substrate decomposition rates and availability of nutrient products for trace gas production from principles which fundamentally couple primary production by plants with decomposition by soil microbes. For example, modeling of C dioxide production in any agricultural ecosystem requires knowledge of the amount and chemical composition of cultivated plant residues, along with soil pH, temperature and variability in water content. The goal here is to highlight these types of commonalities among the reported modeling systems, as well as the diverse capabilities offered by the collection of simulation models as a whole.

The Century Model was originally developed to assist with land planning decisions in the US Great Plains. The model uses a monthly time step to simulate the dynamics of Carbon (C), Nitrogen (N), Phosphorus (P), and Sulfur (S) for different plant–soil systems. Although Century was originally developed for grasslands (Parton *et al.* 1987), the current version of the model has been developed to simulate a variety of ecosystem types, including agricultural crops and temperate and tropical forest systems. The grassland/crop and forest systems have different plant production submodels that are linked to a common SOM and nutrient cycling submodel, which has been fully described before (Metherell *et al.* 1993, Parton *et al.* 1994). In short, the model includes two fractions of litter (metabolic and structural) and three SOM pools (active, slow, and passive), which differ in their potential decomposition rates. In addition, there are residue pools representing different size fractions of woody debris. The model also includes separate state variables for C isotopes (^{13}C, ^{14}C), allowing for use in tracer studies. The forest plant production model divides the tree into leaves, fine roots (< 2mm in diameter), fine branches (<10cm in diameter), large wood (branch and stem wood >10 cm in diameter), and coarse roots (>2mm in diameter), with C and nutrients allocated to the different plant parts using a fixed allocation scheme. Dead leaves and fine roots are transferred to the surface and root residue pools, and are then allocated to structural and metabolic pools. Dead fine branch, large wood, and coarse root pools receive dead wood material from the live fine branch, large wood, and coarse root pools, respectively. Each dead wood pool has a specific decay rate. The dead wood pools decay in the same way that the structural residue pool decomposes, with lignin going to the slow pool and the non-lignin fraction going to the active pool (Metherell *et al.* 1993). In the SOM and nutrient cycling submodel, the active pool represents microbial biomass and metabolites which turn over relatively rapidly (annual time scales), the slow pool consists of partially stabilized SOM constituents with an intermediate turnover time (in the order of decades), while the passive pool represents recalcitrant materials that turn over on time scales of centuries. Separate pools for surface vs. soil locations are maintained for the two litter fractions and the active pool, while the slow and passive pools are represented only within the soil. Various environmental factors (e.g., temperature, moisture), litter quality, soil texture, and management activities affect the parameters controlling decomposition rates and coefficients governing the flow of C, N, S and P between the SOM pools.

The Rothamsted Carbon Model (RothC) was idealized and created to predict how land use and management practice options would affect SOM dynamics in the historic (one of the oldest long-term experiments worldwide) experiment located at the Rothamsted Station, UK. The RothC model (described in detail by Jenkinson *et al.* 1992 and Coleman *et al.* 1997) predicts organic C turnover in non-waterlogged top soils according to soil type, temperature, moisture content and plant cover. It uses a monthly time step to calculate total C, microbial biomass C and Delta^{14}C on a years-to-centuries timescale. In this model, soil organic C is split into four active fractions and one small inert organic matter (IOM) fraction. The four active fractions are decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO) and humified organic matter (HUM). Each fraction decomposes by a first-order process with its own characteristic rate. The IOM fraction is resistant to decomposition. RothC is solely concerned with soil processes and does not contain a sub-model for plant production as does the CENTURY model (Parton *et al.* 1987). The RothC model's main advantage is that it runs on data that are readily available (Smith et al. 1997).

The Terrestrial Ecosystem Model (TEM) is a well-documented process-based ecosystem model that uses spatially referenced information on climate, elevation, soils, vegetation and water availability to make estimates of vegetation and soil C, N pools and fluxes (McGuire *et al.* 1992, Melillo *et al.* 1993, Tian *et al.* 2008). In TEM, net primary production (NPP) is calculated as the difference between gross primary production (GPP) and plant respiration (RA). The GPP represents the uptake of atmospheric CO_2 during photosynthesis and is influenced by light availability, atmospheric CO_2 concentration, temperature, and the availability of water and nitrogen. Plant respiration includes both maintenance and construction respiration, and is calculated as a function of temperature and vegetation C. Annual net C storage (also known as net ecosystem production or NEP) is calculated in TEM as the difference between net primary production (NPP) and heterotrophic respiration. The flux of heterotrophic respiration represents microbially-mediated decomposition of organic matter in an ecosystem and is influenced by the amount of reactive soil organic C, temperature and soil moisture. TEM has been structured to simulate changes in C and N stocks associated with land-cover and land-use changes such as those currently occurring in the Amazon biome. TEM has been used to explore the effects of interannual climate variability on C storage in Amazonian ecosystems (Tian *et al.* 2008). In these studies, TEM predictions were tested against field measurements made in the Amazon. Results of TEM were in reasonable agreement with measurement estimates of (1) short-term, site-specific NEP; and (2) field-based estimates of regional C stocks in vegetation and soils. At three sites in the Amazon, two forests and one Cerrado, the technique of eddy covariance was used to estimate net C exchange between these ecosystems and the atmosphere.

The NASA-CASA model includes interactions of trace gas flux controls: nutrient substrate availability, soil moisture, temperature, texture and microbial activity. The model is designed to simulate daily and seasonal patterns in C fixation, nutrient allocation, litterfall, and soil nitrogen mineralization, as well as CO_2 exchange, in addition to N_2O and NO production, and CH_4 consumption (Potter *et al.* 2001a, 2001b). The fraction of net primary production (NPP), defined as net fixation of CO2 by vegetation, is computed on the basis of light-use efficiency. New production of plant biomass is estimated as a product of intercepted photosynthetically active radiation (IPAR) and a light utilization efficiency term that is modified by temperature and soil moisture. Daily air surface temperature, irradiance, and precipitation together regulate the modeled NPP results, using monthly images of a vegetation cover index from the Advanced Very High-Resolution Radiometer (AVHRR) satellite sensor or the NASA MODIS satellite sensor to estimate changes in leaf cover properties at the land surface (Potter *et al.* 2001b). For the soil C and N component, the NASA-CASA design is comparable to a somewhat simplified version of the CENTURY ecosystem model (Parton *et al.* 1994), which simulates C and N cycling with a set of compartmental difference equations. Predicted emission rates of NO and N_2O from soils are simulated with a simplified application of a conceptual “leaky-pipe” model. The primary controlling factors used in this leaky pipe scheme are gross rates of N mineralization and an index of water filled pore space.

The Denitrification-Decomposition model (DNDC) is a process-oriented simulation model of soil C and N biogeochemistry (Li *et al.* 1992, Li 2000). In DNDC, soil organic C resides in four major pools: plant residue or litter, microbial biomass, active and passive humus. The model contains four interacting sub-models: a) thermal-hydraulic sub-model which uses soil physical properties, air temperature, and precipitation data to calculate soil temperature and moisture profiles and soil water fluxes over time; b) denitrification sub-model which calculates hourly denitrification rates and nitrous oxide and dinitrogen production during periods when the soil has greater than 40% water-filled pore space; c) decomposition sub-model which calculates daily decomposition, nitrification, ammonia, volatilization processes, and C dioxide production (soil microbial respiration); d) plant growth sub-model which calculates daily root respiration, N uptake by plants, and plant growth.

The Generic Decomposition and Yield model (G´DAY) is a linked plant-soil model that incorporates the well-established Century organic matter decomposition model (Comins and McMurtrie 1993). The plant submodel in G'DAY represents the C and N content in foliage, wood (including stems, branches and coarse roots), and fine roots. The soil submodel contains four litter pools of C and N (structural and metabolic, both above and belowground) and three SOM pools of C and N (active, slow and passive). Processes represented include plant C assimilation, plant N uptake, allocation, tissue senescence and N resorption, litter and SOM decomposition, soil N mineralization and immobilization, N input by atmospheric deposition, biological fixation and chemical fertilization, and N loss by leaching or gaseous emission.

GEFSOC-Soil Carbon Modeling System, sponsored by United Nations Global Environment Facility (GEF) (Milne *et al.* 2007), is a system built to provide scientists, natural resource managers, policy analysts, and others with the tools necessary to conduct regional and country-scale soil C inventories. The system is intended to allow users to assess the effects of land use change on soil C stocks, soil fertility, and the potential for soil C sequestration. The GEFSOC system conducts this analysis using three well-recognized models and methods: i) the Century general ecosystem model, ii) the RothC soil C decomposition model, and iii) the IPCC method for assessing soil Cat regional scales (Easter et al. 2007).

Finally, it can be said that the approaches presented here are useful for the general knowledge of the values of C stocks and GHG emissions, usually accompanied by high associated uncertainty, since the purpose of such tools is to provide generic/coarse information and are usually more applicable to contexts of broader inventories and estimates before a given project / action has actually been implemented (i.e. "ex-ante"). Therefore, for the quantification of specific situations of land use change and/or agricultural management practices and adequate monitoring of changes in C stocks and GHG emissions, it is highly recommended that the evaluation be based on data obtained from samples collected in real field conditions, as proposed by the IPCC (2019b).

2 Potential soil C sequestration through the adoption of sustainable management practices

In this third section, the land use cover across the Americas is presented, with emphasis on the main land uses, such as natural vegetation, pasture and agriculture areas. The land use map provides a complete picture of the Americas, allowing for a broad-scale strategic orientation as to where and what type of nature-based solutions can be prioritized to promote soil C sequestration. Certainly, future endeavors should be done to detail this information to regional and local levels.

Land use cover in the Americas

Land use in the Americas is quite diversified, ranging from areas with snow in North America to tropical forests in Central and South America (***Figure 6***). Among the different land uses with forests in the continent, the areas classified as open forest (11.46 km^2 x 10^6 – 1.146 billion ha) are higher than the areas under closed forest (10.57 km^2 x 10^6 – 1.057 billion ha). For the closed and open forest, the evergreen needle-leaved and evergreen broad-leaved are the most representative of these land uses with 7.16 km^2 x 10^6 – 0.716 billion ha and 7.44 km^2 x 10^6 – 0.744 billion ha, respectively (***Table 1***).

FIGURE 6

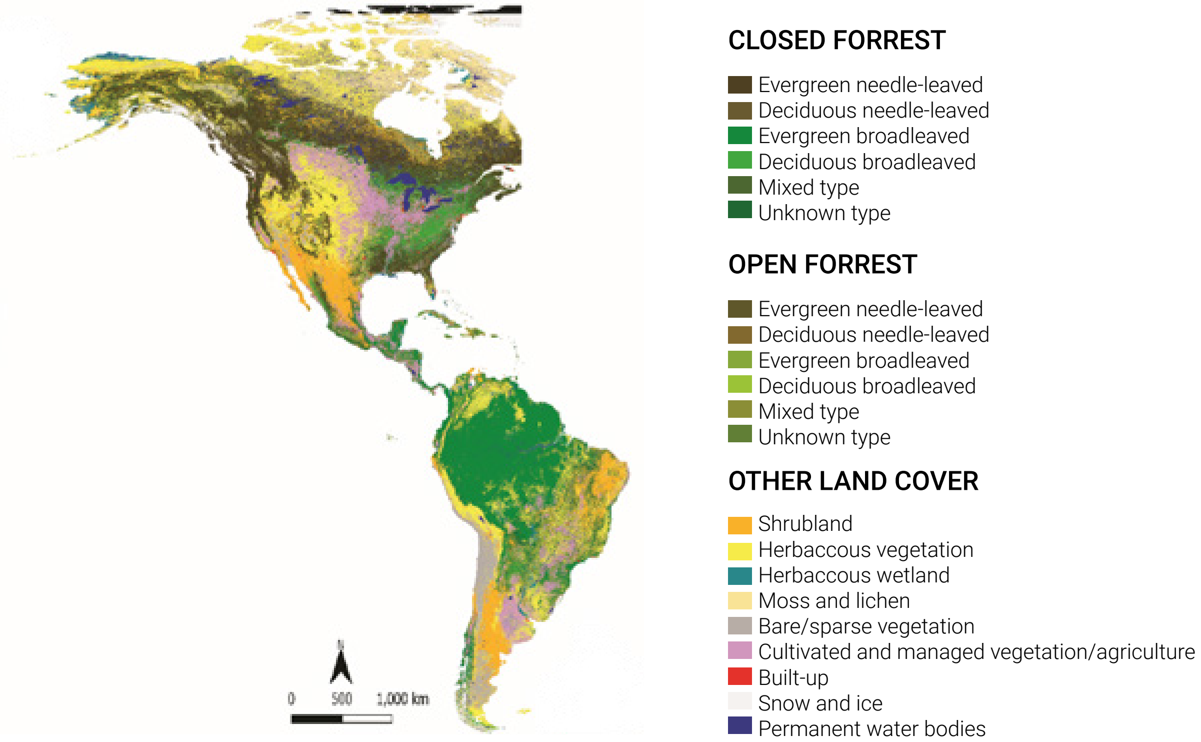

Figure 6. Land use cover of the American continent.
Source: map built based on data from Global Land Cover (https://lcviewer.vito.be/2015).

The total pasture area in the Americas is three times larger than the area classified as agricultural, accounting for 9.05 km^2 x 10^6 (905 million ha). It is important to emphasize that pastures are the main land use "anthropic", where this land use represents 20% of the total area of the other land uses in the Americas. Similar to the land use area under agriculture, pasture areas are predominantly concentrated in North America (3.94 km^2 x 10^6), South America (3.64 km^2 x 10^6) and the Caribbean (0.04 km^2 x 10^6), the difference is that Central America has the smallest pasture area (0,01 km^2 x 10^6). The top five countries with respect to amount of pastures areas in the Americas, in descending order, are United States of America (2.84 km^2 x 10^6), Brazil (1.94 km^2 x 10_6), Canada (1.80 km^2 x 10^6), Argentina (0.85 km^2 x 106) and Mexico (0.45 km^2 x 10^6).

TABLE 1

LAND COVER	AREA (KM^2 X 10^6)
CLOSED FOREST	
Evergreen needle leaved	7.16
Deciduous needle leaved	1.2
Evergreen broad leaved	-
Deciduous broad leaved	0.56
Mixed type	1.65
Unknown type	-
OPEN FOREST	
Evergreen needle leaved	0.19
Deciduous needle leaved	0.52
Evergreen broad leaved	7.44
Deciduous broadleaved	0.01
Mixed type	3.3

Unknown type	-
OTHER LAND COVER	
Shrubland	4.11
Herbaceous vegetation	7.63
Herbaceous wetland	0.59
Moss and lichen	1.1
Bare/sparse vegetation	1.42
Cultivated and managed vegetation/ agriculture	3.4
Rice	0.06
Soybean	0.91
Maize	0.72
Wheat	0.35
Sugarcane	0.14
Coffee	0.05
Grassland	9.05
Built-up	0.24
Snow and ice	0.25
Permanent water bodies	1.47

Source: data from Global Land Cover (https://lcviewer.vito.be/2015) and FAO (2019).

Agricultural lands (croplands) are among the smallest land use areas in the continent, accounting for 3.40 $km^2 \times 10^6$ (340 million ha). These areas represent only 8% of the total area of the other land uses (45.04 $km^2 \times 10^6$ – 4.504 billion ha). Croplands are predominantly located in North America (2.03 $km^2 \times 10^6$; ***Figure 7***). South and Central America have 1.21 and 0.14 $km^2 \times 10^6$ respectively, while the Caribbean has the smallest area (0.02 $km^2 \times 10^6$). Among the crops, annual crops such as soybean (0.91 km^2 x 10^6 - 91 million ha), maize (0.72 km^2 x 10^6 - 72 million ha) and wheat (0.35 km^2 x 10^6 - 35 million ha) are the most cultivated in the Americas. The United States stands out as the major producer of maize (0.33 km^2 x 10^6 - 33 million ha) and wheat (0.15 km^2 x 10^6 - 15 million ha), while Brazil (0.36 km^2 x 10^6 - 36 million ha) is the major producer of soybean. Sugarcane as a semi-perennial crop is cultivated on approximately 14 million ha, of which 10 million ha is concentrated in large-scale fields in Brazil. Other sugarcane producing-countries are Mexico, Colombia and the USA. Among the perennial crops, coffee covers the largest producing area of the continent (5 million ha). Coffee is widely distributed among the Latin American countries, such as Brazil, Colombia, Honduras, Mexico, Peru, Bolivia, Costa Rica, Guatemala, Ecuador and Nicaragua among others.

FIGURE 7

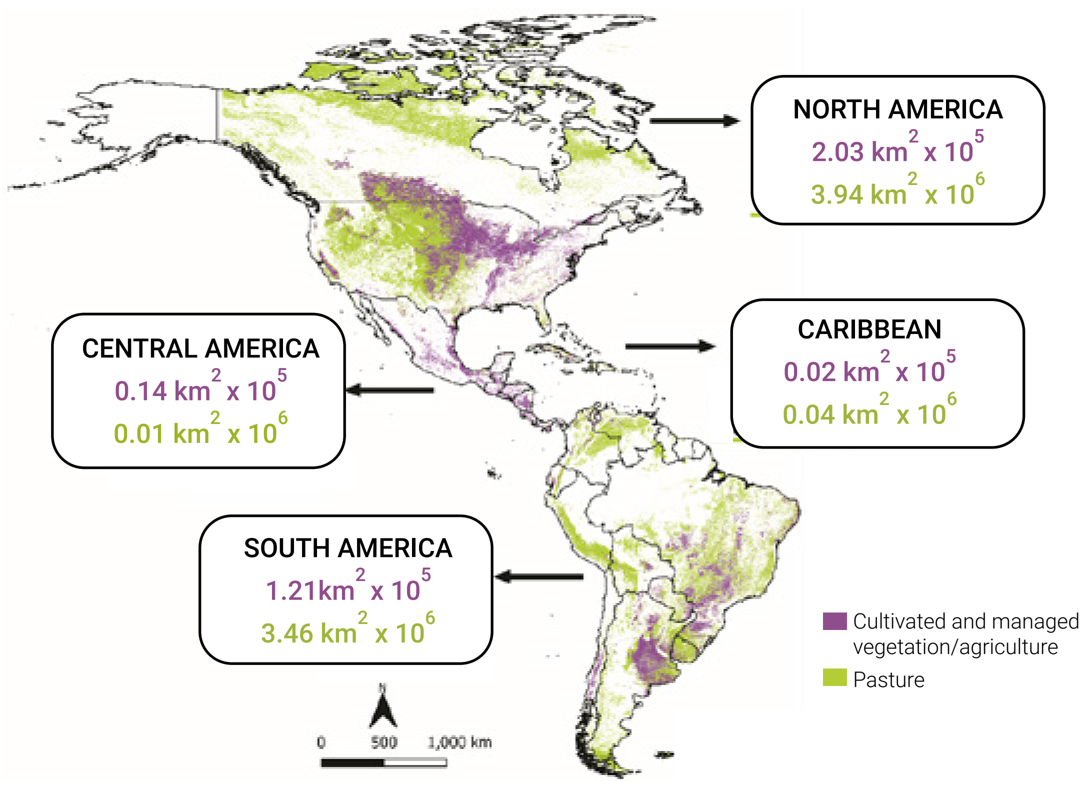

Figure 7. Croplands and pastures in the North, Central, Caribbean and South American regions.
Source: map created based on data from Global Land Cover (https://lcviewer.vito.be/2015).

Current soil carbon stock map (0-30cm)

The diversity of land use and management, soil types and climate conditions was reflected in the wide variability of soil C stock across the Americas (***Figure 8***). Because of this, treating the evaluations of the soil C stock separately can be the right way to analyze the C changes throughout the entire hemisphere. The results showed that Central America and the Caribbean have the highest means of soil C stock, representing 63.30 and 61.35 Mg ha^{-1}, respectively (***Figure 10*** and ***Figure 11***). On the other hand, North and South America presented similar soil C stock of 53.91 and 48.11 Mg ha^{-1}, respectively (***Figures 9*** and ***Figure 12***). It is important to highlight that in South America (***Figure 12***) the soil C stock was below the mean found for the entire Americas (51.28 Mg ha^{-1}), observed in Figure 8.

FIGURE 8

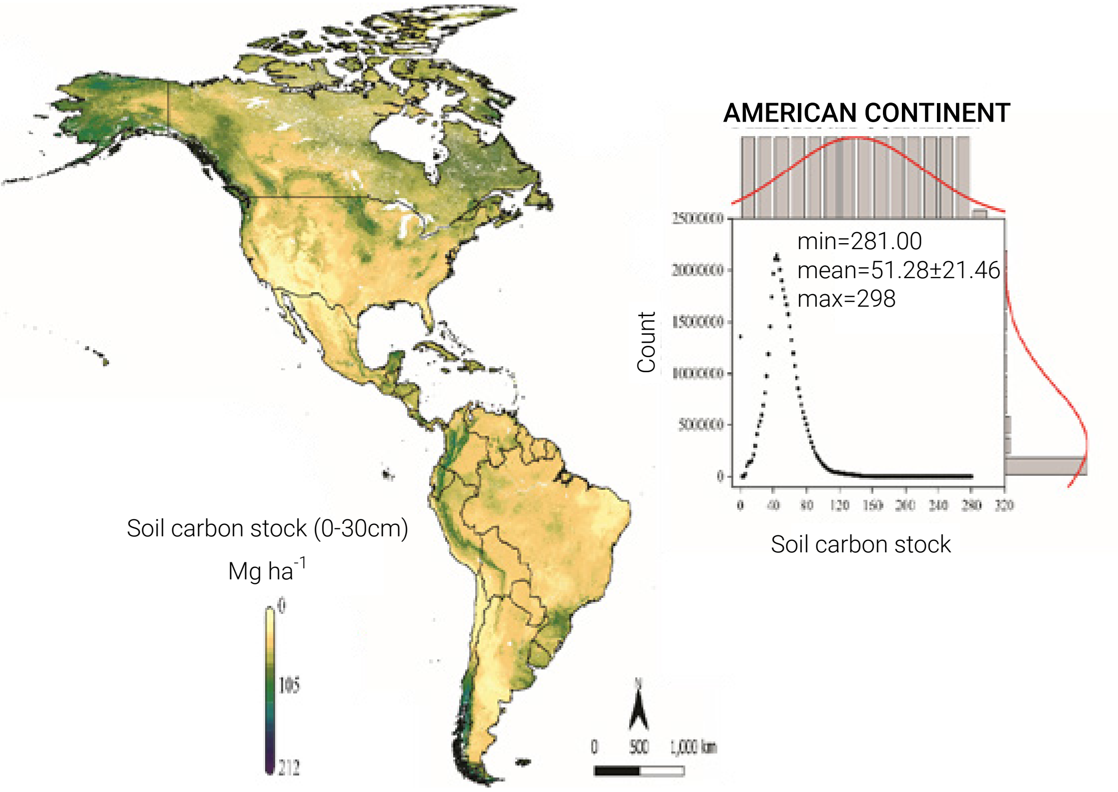

Figure 8. Soil C stocks spatialization and distribution in the Americas.
Source: map built based on data from Soil Grids (https://soilgrids.org/).

FIGURE 9

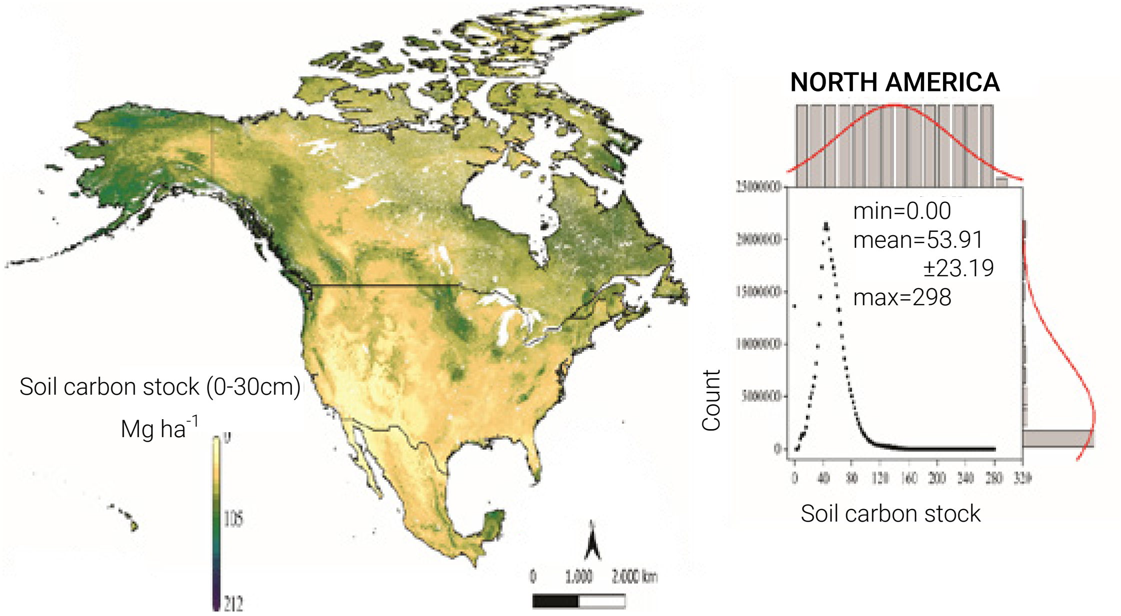

Figure 9. Soil C stocks spatialization and distribution in North America.
Source: map built based on data from Soil Grids (https://soilgrids.org/).

FIGURE 10

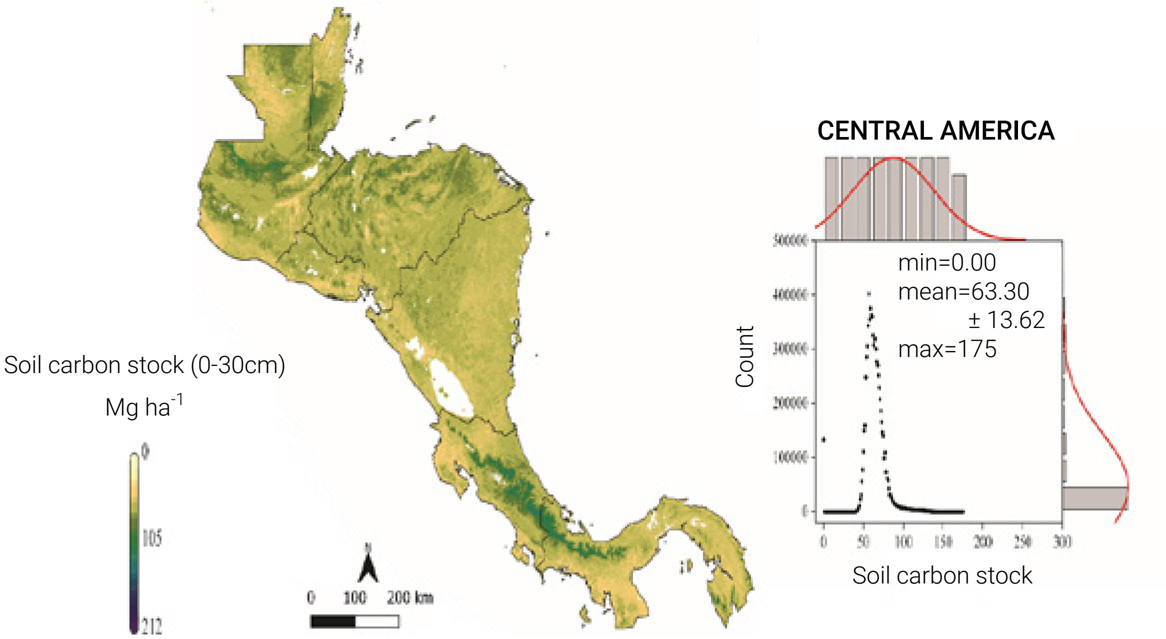

Figure 10. Soil C stocks spatialization and distribution in Central America.
Source: map built based on data from Soil Grids (https://soilgrids.org/).

FIGURE 11

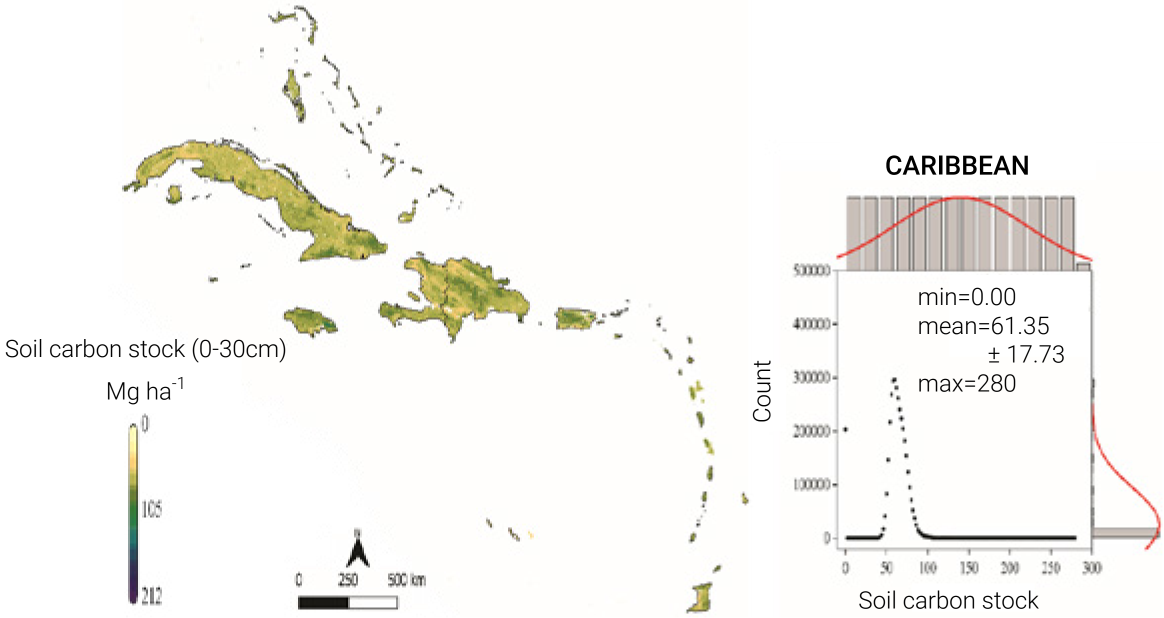

Figure 11. Soil C stocks spatialization and distribution in the Caribbean.
Source: map built based on data from Soil Grids (https://soilgrids.org/).

FIGURE 12

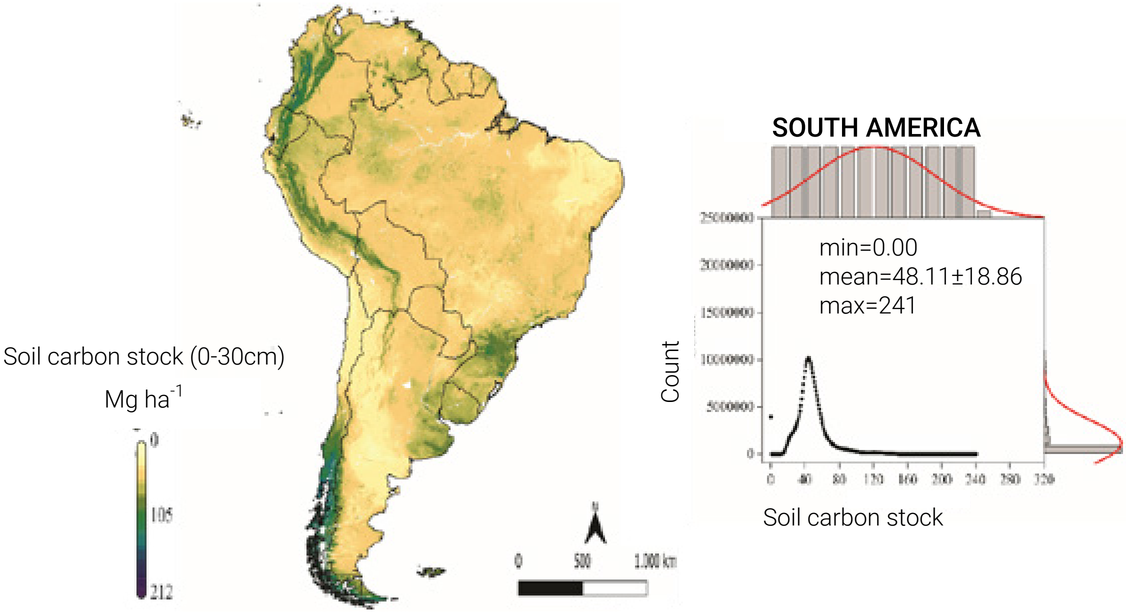

Figure 12. Soil C stocks spatialization and distribution in South America.
Source: map built based on data from Soil Grids (https://soilgrids.org/).

A recent study estimates that global C stocks in cropland soils account for 132 Pg in the 0-30 cm soil depth (Zomer *et al.* 2017). Among the different regions in the world, North America showed the highest soil C stocks (28.07 Pg). By contrast, regions such as Central America have very low amounts of stored soil C (1.22 Pg), besides the high C stock per hectare. In addition, this study points out that despite South America having a fairly large amount of cropland, this region accounts for only a moderate proportion of soil C stocks (9.42 Pg C). Together, the information presented by these authors and the data analyzed in the present study revealed a large potential for soil C accumulation in the Americas.

Sustainable management practices for soil C sequestration

Sustainable soil management practices are adopted with the aim of increasing the soil C stocks and associated ecosystem services. However, the direction and magnitude of the changes induced on soil C stocks depends on the initial soil C conditions (baseline), soil and climate conditions and, particularly, the C balance (i.e., C inputs - C outputs). Eligible sustainable management practices that increment soil C stocks compared to the business as usual practices (already adopted by the farmer) can be represented by the four scenarios (***Figure 11***): a) lands where soil C stocks have reached equilibrium and it is possible to increase levels through sustainable soil management (SSM); b) lands where the soil C stocks is increasing but can be further increased through SSM; c) lands where soil C stocks are declining and it is possible to stop or mitigate losses in soil C stocks through SSM; and d) lands where soil C stocks are declining and it is possible to reverse this fall through SSM (FAO 2020).

FIGURE 13

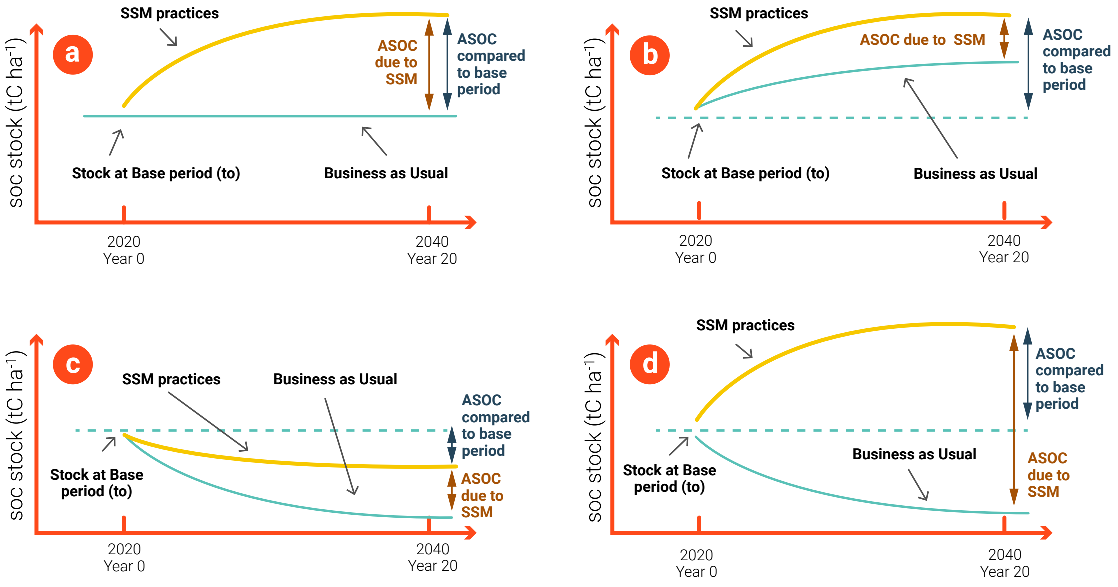

Figure 13. Soil organic C theoretical evolutions under a business-as-usual (BAU) scenario and after the adoption of Sustainable Soil Management (SSM) practices. This depicts a) lands where SOC levels have reached equilibrium and it is possible to increase levels through SSM; b) lands where SOC is increasing but can be further increased through SSM; and lands where SOC is decreasing and it is possible to stop or mitigate losses in SOC levels (c), or even reverse this fall through SSM (d).
Source: FAO (2020)

An overview of the potential soil C accumulation in the Americas through adopting large-scale sustainable management practices in pasturelands and croplands is presented in Table 2. Pasture is the largest agricultural land use, accounting for approximately 900 Mha in the Americas. However, most of the pasture area is poorly managed, is degraded or is in some stage of degradation. Therefore, pasture reclamation is one the most promising nature-based solutions to sequester C and mitigate climate changes (***Figure 12 a-b***). Assuming a conservative scenario, we estimate how much C could be accumulated in the soils in 20 years by implementing sustainable management practices to recover 40% of current pasture areas. We propose the same pasture reclamation goal (40%) for all countries of the region, regardless of the size of the pasture area and management conditions. Our estimate showed an overall potential of soil C accumulation by pasture reclamation in the Americas continent of 1,792Tg C (1.782 Pg C), ranging from 717 to 2,868 Tg (0.717 to 2.868 Pg C) for the 0-30 cm. The highest potential of C accumulation in pasture is observed in the North and South America region, mainly in countries such as the USA, Canada, Brazil, Argentina and Mexico. Nevertheless, since pasture is abundant and widely distributed across the continent (***Figure 7***), almost all the countries have the potential to sequester C in the soil and contribute at some level to mitigate climate change. In addition, pasture reclamation management also improves soil health, land productivity (food production) and consequently farmer incomes. Based on that, we advocated that pasture reclamation should be prioritized in the climate and sustainability agendas of the countries in the next decades.

In croplands, the adoption of conservation tillage is the most widespread sustainable management practice to increase soil C stocks (***Figure 12 c-d***). However, conventional tillage is still the predominant system adopted in the American croplands. In this scenario, we estimated how much C could be accumulated in the soil by expanding no-tillage over 50% of current area cultivated with the main annual crops (corn, soybean, wheat, rice). The results showed that the potential for the American continent is, on average, 888 Tg C (0.888 Pg C), ranging from 529 to 1,247 Tg (0.717 to 1.247 Pg C) for the 0-60 cm depth. Countries such as the USA and Brazil have the largest potential to accumulate C in the cropland soils, but within all American regions, many countries have the potential to accumulate C and contribute to improving soil health and mitigating climate change (***Table 2***).

Figure 12. Pasturelands under degraded processes (a) and with the adoption of sustainable management practices (b) in Mato Grosso state, Brazil, and soybean cultivation over brachiaria mulching in a no-tillage field in Mato Grosso state, Brazil (c), and no-tillage areas with cover crops in Buenos Aires state, Argentina (d). *Photos: Júnior Melo Damian, Rodrigo Trevisan, Alberto Peper.*

Based on the estimate, adopting sustainable management practices (e.g., pasture reclamation and conservation tillage) the potential soil C accumulation is about **2.68 Pg C (1.25 – 4.11 Pg C)**, representing a total of **9.81 Pg CO2eq. (4.56 – 15.06 Pg CO2eq)** in the 20 years. Overall, the results show that annual C accumulation in pasture and agriculture soils have the potential to offset **7.9% (3.7 – 12.2%)** of the total annual global net anthropogenic GHG emissions due to agriculture[2], and **4.1% (1.9 – 6.3%)** of the total annual global net anthropogenic GHG emissions due to agriculture, forestry, and other land use (AFOLU)[3].

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[2] Annual global GHG emissions attributed to agriculture is 6.2 (± 1.4) Pg CO2eq according to IPCC (2019a).

[3] Annual global GHG emissions attributed to AFOLU is 12 (± 2.9) Pg CO2eq according to IPCC (2019a).

TABLE 2. Potential soil C accumulation due to the adoption of large-scale sustainable management practices (SMP) in pasture and cropland areas in the countries of the Americas.

ZONE	COUNTRY	AREA (MILLION HA - MHA)*					SOIL C ACCUMULATION THROUGH SMP (TG C)					
		PASTURE	CROPLAND				PASTURE RECLAMATION§			CONSERVATION TILLAGE		
			RICE	SOYBEAN	MAIZE	WHEAT	LOWER LIMIT	MEAN	UPPER LIMIT	LOWER LIMIT	MEAN	UPPER LIMIT
NORTH AMERICA	Unites States of America	283.95	1.18	35.45	32.89	16.03	227.16	**567.9**	908.64	217.76	**365.53**	513.3
	Canada	180.46	-	2.54	1.43	9.88	144.37	**360.92**	577.47	35.25	**59.18**	83.1
	Mexico	44.97	0.05	0.19	7.12	0.54	35.98	**89.94**	143.9	20.1	**33.73**	47.37
	Subtotal	*509.38*	*1.23*	*38.18*	*41.44*	*26.45*	*407.5*	***1,018.76***	*1,630.02*	*273.11*	***458.44***	*643.77*
CENTRAL AMERICA	Belize	0.2	>0.01	0.01	0.02	-	0.16	**0.4**	0.64	0.1	**0.17**	0.24
	Costa Rica	0.27	0.04	-	>0.01	-	0.22	**0.54**	0.86	0.13	**0.21**	0.3
	Guatemala	0.43	>0.01	0.02	0.92	>0.01	0.34	**0.86**	1.38	2.44	**4.1**	5.76
	Honduras	0.47	0.02	>0.01	0.39	>0.01	0.38	**0.94**	1.5	1.09	**1.84**	2.58
	Nicaragua	0.61	0.07	>0.01	0.28	-	0.49	**1.22**	1.95	0.92	**1.54**	2.16
	Panama	0.2	0.1	>0.01	0.05	-	0.16	**0.4**	0.64	0.41	**0.68**	0.96
	El Salvador	0.03	>0.01	>0.01	0.27	-	0.02	**0.06**	0.1	0.74	**1.24**	1.74
	Subtotal	*2.21*	*0.26*	*0.07*	*1.94*	*0.02*	*1.77*	***4.42***	*7.07*	*5.83*	***9.78***	13.74

CARIBBEAN	Haiti	0.24	0.06	-	0.4		0.19	**0.48**	0.77	1.17	**1.97**	2.76
	Cuba	0.19	0.13	-	0.14		0.15	**0.38**	0.61	0.69	**1.15**	1.62
	Dominican Republic	0.33	0.19	-	0.03		0.26	**0.66**	1.06	0.56	**0.94**	1.32
	Jamaica	0.02	0	-	>0.01		0.02	**0.04**	0.06	0.03	**0.04**	0.06
	Puerto Rico	0.04	>0.01	-	>0.01		0.03	**0.08**	0.13	0.05	**0.09**	0.12
	Trinidad and Tobago	0.05	0.01	-	0.01		0.04	**0.1**	0.16	0.05	**0.09**	0.12
	Montenegro	0.35	-	-	0.01	0.01	0.28	**0.7**	1.12	0.05	**0.09**	0.12
	Guadeloupe	>0.01	-	-			0.01	**0.02**	0.03	0	**0**	0
	Bahamas	0.18	-	-	0.01	0.01	0.14	**0.36**	0.58	0.05	**0.09**	0.12
	Barbados	>0.01	-	-	0.01		0.01	**0.02**	0.03	0.03	**0.04**	0.06
	Saint Lucia	>0.01	-	-	0		0.01	**0.02**	0.03	0	**0**	0
	Grenada	>0.01	-	-	0.01		0.01	**0.02**	0.03	0.03	**0.04**	0.06
	Saint Vincent and the Grenadines	>0.01	0	-	0.01		0.01	**0.02**	0.03	0.03	**0.04**	0.06
	Aruba	0	-	-			0	**0**	0	0	**0**	0
	United States Virgin Islands	>0.01	-	-		-	0.01	**0.02**	0.03	0	**0**	0
	Antigua and Barbuda	>0.01	-	-	>0.01	-	0.01	**0.02**	0.03	0.03	**0.04**	0.06
	Dominica	>0.01	-	-	>0.01	-	0.01	**0.02**	0.03	0.03	**0.04**	0.06
	Cayman Islands	0	-	-	-	-	0	**0**	0	0	**0**	0
	Saint Kitts and Nevis	0	-	-	-	-	0	**0**	0	0	**0**	0
	Saint Martin	-	-	-	-	-	0	**0**	0	0	**0**	0
	Turks and Caicos Islands	>0.01	-	-	-	-	0.01	**0.02**	0.03	0	**0**	0
	British Virgin Islands	0	-	-	-	-	0	**0**	0	0	**0**	0
	Anguilla	0	-	-	-	-	0	**0**	0	0	**0**	0
	Montserrat	0	-	-	-	-	0	**0**	0	0	**0**	0
	Subtotal	*1.49*	*0.4*	*0*	*0.67*	*0.02*	*1.19*	***2.98***	*4.77*	*2.77*	***4.66***	*6.54*

SOUTH AMERICA	Guyana	1.51	0.17	0	> 0.01	-	1.21	**3.02**	4.83	0.46	**0.77**	1.08
	French Guiana	> 0.01	-	-	-	-	0.01	**0.02**	0.03	0	**0**	0
	Peru	32.83	0.44	0.01	0.46	0.13	26.26	**65.66**	105.06	2.65	**4.44**	6.24
	Paraguay	3.58	0.14	3.51	1.07	0.43	2.86	**7.16**	11.46	13.11	**22**	30.9
	Suriname	0.14	0.06	> 0.01	> 0.01	-	0.11	**0.28**	0.45	0.2	**0.34**	0.48
	Uruguay	10	0.16	1.1	0.07	0.19	8	**20**	32	3.87	**6.49**	9.12
	Venezuela	19.59	0.17	> 0.01	0.44	0.01	15.67	**39.18**	62.69	1.6	**2.69**	3.78
	Argentina	85.14	0.2	16.32	7.14	5.82	68.11	**170.28**	272.45	75.04	**125.96**	176.88
	Bolivia	17.17	0.17	1.36	0.46	0.2	13.74	**34.34**	54.94	5.57	**9.36**	13.14
	Brazil	193.58	1.87	34.78	16.13	2.08	154.86	**387.16**	619.46	139.64	**234.4**	329.16
	Chile	8.89	0.03	0	0.09	0.24	7.11	**17.78**	28.45	0.92	**1.54**	2.16
	Colombia	8.95	0.53	0.03	0.39	> 0.01	7.16	**17.9**	28.64	2.44	**4.1**	5.76
	Ecuador	1.78	0.3	0.02	0.37	> 0.01	1.42	**3.56**	5.7	1.78	**2.99**	4.2
	Subtotal	*383.17*	*4.24*	*57.15*	*26.64*	*9.12*	*306.54*	***766.34***	*1,226.14*	*247.29*	***415.1***	*582.9*
AMERICA	**Total**	896.25	6.13	95.4	70.69	35.61	717	**1,792.50**	2,868.00	529.01	**887.98**	1,246.95

*The area of pasture and main annual crops are based on data available of 2019 in FAOSTAT (http://www.fao.org/faostat/en/#data)

§The scenario for pasture reclamation considered recovering 40% of current pasture area (linearly among the countries). The soil C stock accumulation rate used in the estimate was 0.25 Mg C ha^{-1} ha^{-1} (0.10 – 0.40 Mg C ha^{-1} ha^{-1}) based on data compiled from 89 studies performed by Conant *et al.* (2017). The time spam considered to reach steady-state was 20 years (IPCC 2014).

‡ The scenario for adoption conservation tillage (no-tillage) considered to converting 50% of current cropland area from conventional tillage to no-tillage (linearly among the countries). The soil C stock accumulation rate used in the estimate was 0.42 Mg C ha^{-1} ha^{-1}(0.25 – 0.59 Mg C ha^{-1} ha^{-1}) based on data compiled from 121 studies performed by Nicoloso and Rice (2021). The time spam considered to reach steady-state was 20 years (IPCC 1997).

It is worth noting that our estimate included the potential pasture to sequester C only in the first 30 cm of the soils. However, considering the vigorous and deep root system of the grasses, this potential may be higher if the 0 - 1 m depth is considered. A global analysis showed recently that approximately 53% of the C stored in the first meter of the soil is allocated in the 30-100 cm layer, and about 20% of the new C incorporated in the soils is found in this deeper soil layer (Balesdent *et al.* 2018). It is also applicable to cropland, where no-tillage soils have the potential to sequester C not only in the surface layer, but also in deeper layers (0 - 1 m) (Nicoloso and Rice 2021).

Finally, in addition to pasture reclamation and conservation tillage, there are multiple other promising sustainable management practices that could be adopted across the Americas to promote soil C sequestration, such as cover crops, organic amendments, agricultural integrated systems (i.e., silvopastoral and integrated crop-livestock-forest systems), and forest restoration, among others.

The segment provided examples of how those sustainable management practices can promote soil C sequestration across the American regions and countries.

Case studies

Cover crops

Conservation agriculture is based on three principles: no soil disturbance by tillage, permanent soil cover and crop rotation. The no-tillage system is widely used around the world, but seven of the top10 countries with the largest no tillage areas are located in the Americas – 1) USA, 2) Brazil, 3) Argentina, 4) Canada, 6) Paraguay, 9) Bolivia and 10) Uruguay (Kassan et al. 2019). It is known that no tillage can be an efficient management system to increase the soil C stocks, but the rate of C sequestration depends on the association of NT with increased crop frequency and the inclusion of cover crops (Nicoloso and Rice 2021) as shown in the Table 2. Adoption of cover crops is one important pillar of conservation agriculture. In a global meta-analysis, Jian *et al.* (2020) found that including cover crops into rotations significantly increased soil C stocks, with an overall mean change of 15.5%. This same study highlights that cover crops in temperate climates had greater changes in soil C accumulation (18.7%) than those in tropical climates (7.2%). These results indicate that soil C accumulation rates induced by introducing cover crops can be variable due to specific soil and climate conditions across the Americas (***Box 1***).

BOX 1

The use of cover crops is a management practice that can potentially increase the soil C accumulation and other soil health indicators.

Radish growing as a cover crop in no-tillage soils in Ames, Iowa state, USA. *Photo: Maurício Roberto Cherubin*

In temperate climate regions, such as North America, cover crops increase soil organic C stocks (0.1 to 1 Mg ha^{-1} y-^{1}) with the magnitude depending on biomass amount, years in cover crops, and initial soil C level (Blanco Caqui et al. *2015). Recently, a large-scale farm-led trial conducted in 78 farms across nine US states revealed that cover crops impact positively on multiple soil health indicators, including small, but significant increments in the soil organic C contents, even in the short term (2-5 years) (Wood and Bowman 2021).*

Pasture restoration through integrated systems

Over the past decades, other alternatives in management practices for rehabilitating degraded pasturelands have emerged, as is the case with the integrated systems. In ***Box 2***, there is an example of the adoption of the silvopastoral system in Colombia.

BOX 2

The adoption of the silvopastoral system has stood out as a feasible alternative to restore land productivity, soil health and C sequestration in areas previously occupied by extensive, poorly-managed pasturelands.

Silvopastoral systems in the Amazon region near Florencia, Caquetá state, Colombia. *Photo: Andrés Olaya-Montes*

Pasture reclamation through the silvopastoral system can be implemented across the different agro-ecological regions of the Americas. In each region, the system can be designed using native and well-adapted tree species to boost soil C sequestration and other benefits. As on example, recent studies conducted in the Amazon region of southern Colombia

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BOX 2

(Caquetá state), the adoption of the silvopastoral system has promoted soil C accumulation of 0.26 Mg ha^{-1} y^{-1}, as well as enhanced the chemical, physical and biological soil properties (Olaya-Montes et al. *2021, Polanía-Hincapié* et al. *2021). To have an idea of the potential of silvopastoral systems, if we consider the Colombian pasture area (0.09 km^2 x 10^6), the adoption of this management system can accumulate 2 Tg y^{-1}.*

The integrated crop-livestock-forestry-system (ICLFS) is another type of integrated systems that can be adopted as a strategy for restoring degraded pastures (***Box 3***).

BOX 3

Integrated crop-livestock-forestry system (ICLFS) has been successfully adopted by farmers across the Americas as a system to intensify and diversify the production system. It consists of growing tree species simultaneously with commercial annual crops (e.g., soybeans, maize and beans) and pasture to feed animals in rotation in the same area.

Integrated crop-livestock-forest system in São Carlos, São Paulo state, Brazil. *Photo: Wanderlei Bieluczyk*

BOX 3

Integrated crop-livestock-forest systems can be designed using native or exotic trees such as eucalyptus. In general, native trees have a slower growth rate than exotic species. It implies lower shading and consequently, allows for the growing of annual crops for more years in the area between the tree lines. On the other hand, exotic trees grow faster and accumulate more C in the biomass, and can generate income (through the sale of wood) to the farmer every 5-7 years. As an example, the conversion of pastures to ICLFS promotes increases in soil C stocks of 1.44 to 1.72 Mg ha^{-1} y^{-1} *in Brazil (de Freitas* et al. *2020, Sarto* et al. *2020). Scaling up the rates of these soil C gains to the Brazilian area with pastures (1.94* km^2 *x* 10^6*), the adoption of the ICLFS have the potential of soil C accumulation of 279 to 333 Tg* y^{-1}*.*

Sustainable management practices in coffee fields

Coffee is one of the most important commodities produced in Latin America. Among the top-10 largest coffee-producing countries, five are located in Latin America (Brazil, Colombia, Honduras, Peru and Mexico). In addition, coffee is also important for many other countries such as Guatemala, Costa Rica, Ecuador and Nicaragua. There is a wide diversity of coffee production systems in the hemisphere, ranging from large-scale monoculture fields in Brazil to smallholder coffee agroforests in Colombia, Costa Rica, Peru, among others. The potential of introducing sustainable management practices in the coffee field is illustrated in ***Box 4***.

BOX 4

Sustainable management options adopted in coffee fields across the region includes agroforestry systems, organic amendments (manure and residues from tree pruning), and inter-row cover cropping to promote soil C sequestration in coffee fields.

BOX 4

Coffee farm in Acevedo, Huíla state, Colombia. *Photo: Juan P. C. Bermeo*

In the Lake Altitlán region of Guatemala, Central America, for example, Schmitt-Harsh et al. *(2012) evaluated C pools (aboveground biomass, coarse roots and soil C) of smallholder coffee agroforests in 61 plots. They compared the results with a mixed dry forest system. Results revealed that even the coffee agroforestry had lower total C stock than forest, individual tree and soil C stocks were not significantly different suggesting that agroforest shade trees play an important role in facilitating C sequestration and soil conservation. In Costa Rica, Chatterjee et al. (2020) measured soil C stocks (0-10, 10-30, 30-60, and 60-100 cm depths) in two long-term (17 years) shaded perennial coffee agroforestry systems: i) coffee grown conventionally (with chemical fertilizers) and organically (without chemical fertilizers) under two shade trees, Erythrina poeppigiana and Terminalia amazonia; ii) Sun coffee (sole stand of coffee without shade). The results showed no changes in soil C stock within coffee agroforestry systems and sun coffee fields. However, organic management of coffee*

BOX 4

under heavily pruned E. poeppigiana, with pruned litter returned to soil, increased soil C stocks for 0-10 cm depth. In addition to those examples from Central America, there is a large body of scientific evidence showing the potential of sustainable management practices for increasing C stocks (soil and biomass) for other countries of Latin America.

Biochar application in soil for C sequestration and potential GHG emission reduction

Biochar is the product of biomass pyrolysis and has been applied to the soil with the purpose of improving soil health and increasing soil C stocks (Lehmann *et al.* 2006), especially in tropical regions (Carneiro *et al.* 2021). Biochar may not only increase soil C content (Fatima *et al.* 2021) but may also have the potential to decrease GHG emissions, especially N_2O (Guenet *et al.* 2021). However, an increase or no effect on N_2O efflux has also been reported (Spokas and Reicosky, 2009, Scheer *et al.* 2011). These variable responses of soil N2O efflux to biochar amendments have been attributed to different mechanisms. Biochar addition may affect N2O emissions by changing soil ammonium and nitrate concentration (Cheng *et al.* 2008), decreasing soil bulk density (Karhu *et al.* 2011), facilitating N2O consumption in the terminal step of denitrification (Cayuela *et al.* 2014) and adding labile C and N compounds to the soil (Spokas and Reicosky 2009).

Considering the potential of biochar application for mitigating GHG emissions in tropical areas (Rittl *et al.* 2015, Guenet *et al.* 2021), the influence of increased temperature on the N_2O emissions of biochar-amended soils requires investigation (***Box 5***). Little information is available for the interactive response of tropical soil on soil C sequestration and N_2O emissions changes and biochar addition rates (Bamminger *et al.* 2017, Xu *et al.* 2021).

BOX 5

Biochar application has been widely recommended as a potential solution to tackle the challenges of food security and climate change in agroecosystems, but the effective sizes of biochar application on crop yield, soil C sequestration, and global warming potential (GWP) shows great uncertainties (Xu et al*. 2021). Therefore, results for tropical soil conditions are still inconclusive and display variations and the underlying mechanisms explaining the effect of biochar-soil interaction include biochar properties and soil biotic and abiotic conditions.*

Experiments to produce, characterize and apply biochar in sugarcane fields in Brazil. *Photo: Carlos E.P. Cerri*

Scanning electron micrograph of a cross section of a sugarcane biochar (top left - Photo: Thalita F. Abbruzzini) and biochar application in the field (top right and bottom - Photos – Carlos E.P. Cerri)

Natural forest restoration

Natural forest restoration is one of the most important pathways to remove CO2 from the atmosphere in the coming decades (***Box 6***). According to IPCC projections, around one-quarter of the atmospheric C necessary to limit global warming to 1.5°C above pre-industrial levels (IPCC 2018) could be stored by adding up to 24 Mha of forest every year from now until 2030.

BOX 5

International initiatives on forest restoration have been promoted around the world. For example, the Boon Challenge, launched in 2011 by the German government and the IUCN, involves 61 countries (29 located in the Americas) and has the goal of bringing 150 Mha of degraded and deforested landscapes into restoration by 2020 and 350 Mha by 2030 (https://www.bonnchallenge.org/). More recently, the UN Decade on Ecosystem Restoration (2021-2030) has as a target collectively built a broad-based global movement to ramp up restoration and put the world on track for a sustainable future (https://www.decadeonrestoration.org/).

A young tropical forest restoration planting set in pastureland previously used for extensive cattle ranching in the state of Rio de Janeiro, Brazil.
Photo: Pedro Brancalion

However, forest restoration cannot be based (predominantly) on plantations of commercial trees, which are much poorer at storing C than are natural forests (Lewis et al. *2019). Efforts need to be made to stop illegal deforestation, and promote current initiatives (see Initiative 20x20 (https://initiative20x20.org/), of which 17 Latin American countries are members) and new initiatives on natural forest restoration across the countries of the Americas, from Canada to Chile.*

Final remarks

The take-home messages from this document are:

- Soil is the most important C pool in the biosphere, with three times more C than the vegetation and atmosphere;
- Depending on the land use and/or management practices soils can act as a C source (emitting CO2into the atmosphere) or as a sink (sequestering CO2 removed from the atmosphere);
- Healthy and re-carbonized agricultural soils are part of the solution to delivering food and climate security;
- Sustainable soil C sequestration practices and well-oriented political agendas need to be scaled up in country-level blocks to contribute to climate change mitigation;
- There are several approaches to assess soil C sequestration and GHG emissions, ranging from site-specific field measurements to mathematical tools and simulation models;
- Living Soils of the Americas (LiSAm) was launched on the 5th of December, 2020 by the Inter-American Institute for Cooperation on Agriculture (IICA) and the Carbon Management and Sequestration Center at The Ohio State University (CMASC);
- LiSAm is an extensive network involving governments, international organizations, universities, the private sector and civil society organizations that will join efforts to curb land degradation, and consequently to promote soil health, C sequestration and other associated benefits to people;
- The surface area of the Americas covered with agriculture (croplands) is among the smallest land use areas in the hemisphere (3.40 km^2 x 10^6), with soybean (0.91 km^2 x 10^6), maize (0.72 km^2 x 10^6) and wheat (0.35 km^2 x 10^6) being the main annual crops, sugarcane (0.14 km^2 x 10^6) the main semi-perennial crop and coffee (0.05 km^2 x 10^6) the main perennial crop;
- Pastures are three times bigger than the area classified as agriculture, accounting for 9.05 km^2 x 10^6 (905 million ha). This land use is predominantly concentrated in North America (3.94 km^2 x 10^6), South America (3.64 km^2 x 10^6) and the Caribbean (0.04 km^2 x 10^6), with Central America being the smallest area (0.01 km_2 x 10^6).

- We estimated an average soil C accumulation of 51.28 Mg ha^{-1} in the Americas for the 0-30 cm layer (Central America: 63.30 Mg ha^{-1}; Caribbean: 61.35 Mg ha^{-1}; North America: 53.91 Mg ha^{-1}; South America: 48.11 Mg ha^{-1});
- Examples of the practical and feasible sustainable management practices to be promoted across the Americas region include: conservation tillage, grazing management, organic amendments (manure, agroindustrial waste and biochar), cover cropping, mulching, fertility management, integrated agricultural systems (agroforestry, silvopastoral, crop-livestock-forest systems), water management among others;
- Based on our estimate, adopting only two large-scale sustainable management practices (i.e., pasture reclamation and conservation tillage) the potential soil C accumulation in the countries of the Americas is about 2.68 Pg C (1.25 – 4.11 Pg C), representing a total of 9.81 Pg CO_2eq. (4.56-15.06 Pg CO_2eq) over 20 years. This represents a potential to mitigate about 7.9% (3.7 - 12.2%) of the total annual global net anthropogenic GHG emissions due to agriculture and 4.1% (1.9 - 6.3%) of global emissions due to agriculture, forestry, and other land use.
- Sustainable management practices suggested by the LiSAm initiative can guide new protocols for curbing land degradation, promoting soil health and soil C sequestration in the Americas.

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