ANALYTICAL METHODOLOGIES AS TOOLS FOR EVALUATING CARBON SEQUEST IN SOILS IN SEMIARID REGIONS: A SYSTEMATIC REVIEW

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Abstract: The objective of this study was to analyze and evaluate in scientific articles methodologies used in quantifying soil organic carbon (SOC) in semi-arid regions, showing that it is essential to quantify the carbon balance in the soil not only to evaluate the potential of the reservoir, but also to define management strategies for mitigating climate change. A systematic review was carried out in databases considering publications between 2019 and 2023, identifying 47 works. After applying the exclusion criteria, 04 works were analyzed. It is concluded that the methodologies used are useful tools for evaluating carbon sequestration in different types of soils through the quantification of SOC; the technological limitations of each method did not restrict the objective evaluation of the work.

Keywords: Soil; Semi-arid; Climate Change; Carbon Sequestration.

METODOLOGIAS ANALÍTICAS COMO FERRAMENTAS PARA AVALIAÇÃO DE SEQUESTRO DE CARBONO EM SOLOS DE REGIÕES SEMIÁRIDAS: UMA REVISÃO SISTEMÁTICA

Resumo: O objetivo deste estudo foi analisar e avaliar em artigos científicos metodologias utilizadas na quantificação de carbono orgânico no solo (SOC) em regiões semiáridas, mostrando-se fundamental quantificar o balanço de carbono no solo não apenas para avaliar a potencialidade do reservatório, mas também para definir estratégias de gestão na mitigação das alterações climáticas. Foi realizada revisão sistemática em bases de dados considerando publicações entre 2019 e 2023, identificando 47 trabalhos. Após aplicação dos critérios de exclusão, foram analisados 04 trabalhos. Conclui-se que as metodologias utilizadas são ferramentas úteis para avaliação de sequestro de carbono em diferentes tipos de solos por meio da quantificação de SOC; as limitações tecnológicas de cada método não restringiram a avaliação objetiva do trabalho.

Palavras-chave: Solo; Semiárido; Mudanças Climáticas; Sequestro de Carbono.

1. INTRODUCTION

Climate change felt across the globe has become the most important debate of the last decade. According to the report from the Intergovernmental Panel on Climate Change (IPCC), from 1850-1900 to 2006-2015, the average air temperature at the Earth's surface has already increased by 1.53°C, while the global average temperature (Earth and ocean) increased by 0.87°C. This has occurred mainly due to excess emissions of carbon dioxide (CO_2) and other gases, such as methane (CH_4) and nitrous oxide (NO_X) [1].

The Agriculture, Forestry and Other Land Use (AFOLU) sector is responsible for just under 34% of global anthropogenic greenhouse gas (GHG) emissions, which are mainly driven by deforestation and livestock emissions, in addition to the use of nitrogen fertilizers. Agriculture-related carbon dioxide emissions represent about 11% of global greenhouse gas emissions [1,2].

The growing interest in promoting increased C sequestration in soil seeks to mitigate the high levels of CO_2 in the atmosphere, in addition to being a sustainable alternative in the recovery of the majority of agricultural soils previously depleted in terms of organic matter. It is worth highlighting that pedological reservoirs (soils) are of great importance in the biogeochemical carbon cycle. Soils have enormous potential to mitigate climate change through the sequestration of soil organic carbon (SOC), with soil carbon reserves at depths greater than 1m (~1600 Gt) estimated to be twice that of atmospheric carbon (~ 800 Gt) [3,4].

The carbon stock in the soil can be influenced by numerous factors, such as: soil type, vegetation/biomass, climate, topography, living organisms, management and use practices. However, rapid and frequent changes in land use around the world play a crucial role in changing SOC levels, thus becoming a significant determinant of soil organic carbon storage potential, with significant implications for the environment and climate. Due to these factors, adequate assessment through precise soil organic carbon fixation methodologies is a complex activity, seeking to evaluate and/or quantify changes in land use and/or adoption of management practices [5].

Arid and semi-arid regions constitute 36% of the total land area, present in more than 80 countries and with 40% of the global population. Consisting of abundant soils and photothermal resources, they are the main regions of food production. As a result there is great pressure from anthropic activities in these regions, leading to soil degradation, increased CO_2 emissions and desertification. Due to various natural and anthropogenic factors that affect agricultural production, many semi-arid regions suffer from food insecurity for the local population [6].

In this work, a systematic review was carried out related to studies on soils in semi-arid regions and the advancement of research and methodologies that quantify carbon sequestration rates in soils, in order to have an alternative to mitigate the consequences of global climate change. That way, the Preferred Reporting Systematic Reviews and Meta-Analyses (PRISMA) guidelines and procedures were followed as the protocol for the present review [7].

2. METHODOLOGY

The methodology used in this work began with the search for articles in different databases such as Scopus, Web of Science and Scielo. Works of the “Research Article” type, published between 2019 and 2023 (a period of five years), were considered. The review was limited to English as the main language and the terms/keywords were applied together in the research, using the connective “AND”, to them: (“soil”) AND (“carbon sequestration”) AND (“semi -arid”) AND (“climate change”).

Exclusion criteria were adopted in the previously selected papers, with the aim of a more careful selection in order to prioritize works with greater focus for the selected terms. Therefore, the following Exclusion Criteria (EC) were applied to the works found in the databases:

EC-**1:** Studies that do not contain the words “soil” AND “carbon sequestration” AND “semi-arid” AND “climate change” in the abstract.

EC-**2:** Studies that do not mention, in the abstract, the methodologies used to quantify carbon in soils.

In the first stage, papers were selected from the databases following the inclusion criteria for key terms. The next stage followed the reading of the abstracts, where the exclusion criteria would be applied, which selected works were analyzed in more detail. The last stage followed the complete reading of the selected works, where we sought to understand the relationships between the research, global intersection and research opportunities. Therefore, the procedures were adopted based on the flowchart developed by PRISMA [7].

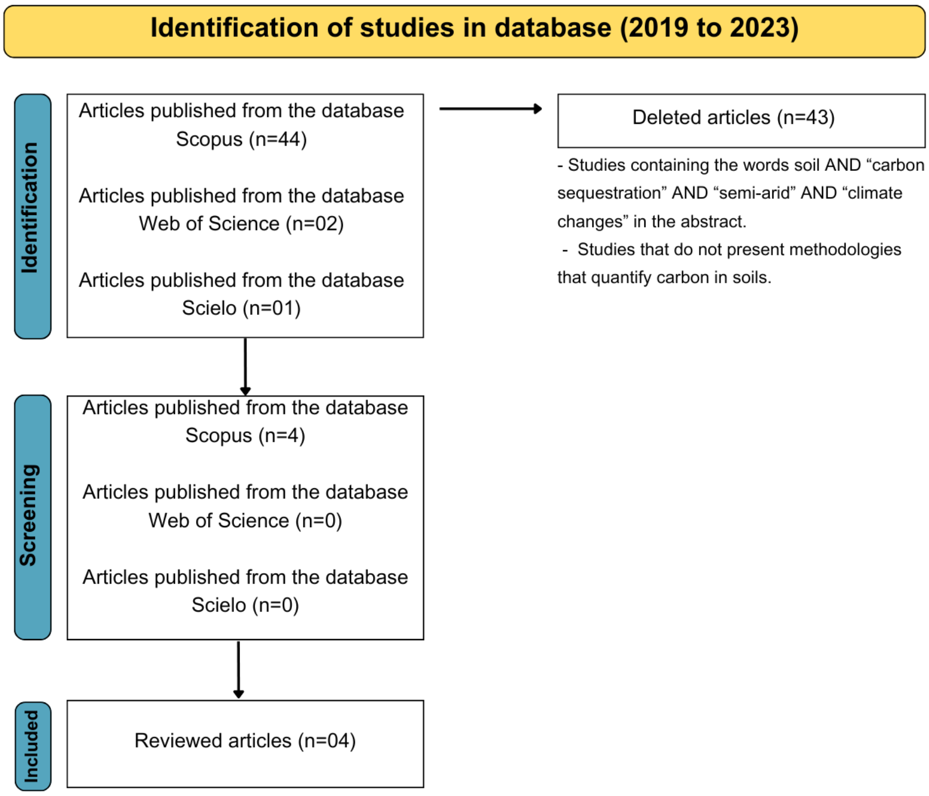
3. RESULTS AND DISCUSSION

The systematic search in its first selection stage identified a total of 47 works, totaling the three databases (Scopus, Web of Science and the Scielo). After applying the first exclusion criterion, studies that did not contain the chosen terms in their abstracts were excluded (n=18), leaving 25 papers. In the papers selected in the first stage, the second exclusion criterion was applied, leaving 04 papers that contained information, in the abstract, about the methodologies used to quantify carbon in the soils studied (Figure 1). We identified the relationships, research methodologies, place of study and place of publication, opportunities and applied technologies from these works selected (Table 1).

The formation of carbon stocks in vegetation occurs through the absorption and fixation of CO_2 from the atmosphere into biomass (photosynthesis). Then, the carbon is incorporated to the soil (organic matter) by roots exudates, roots development and plant death. The selected papers, the methods used to quantify the carbon content in soils were tested on the most diverse types of vegetation, such as dense trees and native vegetation, highlighting a strong relationship between carbon stock in the soil and vegetation/biomass above it [4,8,9].

The selection of the methods that will be most appropriate for any carbon quantification project must consider several factors, including the nature of the soils examined, the accuracy of the method and the costs of the analysis. It is worth highlighting that analytical procedures recover all forms of carbon, from the conversion of these forms to CO_2, using dry or wet combustion [1,10].

Figure 1 - Diagram of the systematic review carried out in this study, according to PRISMA (Adapted from Page *et al.* (2020) [8])



Soil carbon analysis by dry combustion is the direct method used by the IPCC (Intergovernmental Panel on Climate Change), considered as the standard method. However, the high cost of analysis limits its use for small-scale research or monitoring carried out by small farmers. Thus, it has been observed that new methods have been proposed for determining the carbon content in soils [1,4].

One of the methods used in the selected papers is related to dichromate oxidation, also called Walkey & Black method. The general principle of the method is based on the oxidation of C in organic form with dichromate ions in an acidic medium and determination of the material easily oxidizable. This method is most appropriate for evaluating soil fertility in routine analysis laboratories. Carbon is determined only in organic form, since organic C is easily oxidizable. The Walkley & Black method has some limitations, being a method not suitable for soils with a significant presence of inorganic C (such as calcium carbonates) and generating residues that are difficult to manage, for example, chromium and sulfuric acid. Therefore, carbon concentration in soils measured through wet oxidation is simple to perform, low cost, does not require the use of specialized equipment, but does not promote complete oxidation of organic carbon in the soil, not reaching the elemental forms of carbon. Several modifications of this method are proposed, such as heating the sample, which appears to lead to more accurate results [14,15].

Mid-infrared spectroscopy (MIR) is a relatively quick method, which does not require sample preparation, allowing qualitative analysis of organic compounds. MIR involves the spectral interpretation of the chemical structures of soil samples and is more suitable for qualitative purposes [15,16].

Table 1 - Works identified and selected for the systematic review

Reference	Journal	Country	Methodology[1]	Considerations
Gupta *et al.* (2019) [10]	Current Science	India	Walkley & Black	- Estimation of the impact of tree density in two distinct areas, one with 333 trees and the other with 666 trees, of the *Hardwickia Binata Roxb* species. Analyzing the potential for soil carbon sequestration in an agroforestry system. The total carbon sequestered (tree biomass below and above ground and soil organic carbon) was higher in the area with the highest tree density.
Sabetizade, *et al.* (2021) [11]	Catena	Iran	Mid-infrared spectroscopy (MIR)	- Performance of MIR spectroscopy for regional-scale SOC[2] prediction for remote landscapes in Iran. - The high performance of the developed models indicates the high potential of MIR spectroscopy for predicting SOC in data-poor areas
Chen, *et al.* (2022) [12]	Quaternary Sciences	China	Measurement of total organic carbon content (TOC)	- Reconstruction of temporal and spatial distribution of SOCD[3] during the Holocene. - Carbon density is closely related to climate during the Holocene.
Zhang, *et al.* (2023) [13]	Environmental Research	China	Extreme Gradient Boosting (XGBoost)	- The study, based on the NDVI[4] trend, points out that the area of vegetation recovered in this region is much larger than the area degraded from 2001 to 2018. In contrast, when applying the chosen method, the prediction of future vegetation growth and the capacity of carbon sequestration in most areas showed a decreasing trend. Data that prove the need for protective management for the local ecological environment.

[1]Methodology used to quantify carbon in the soil; [2]SOC = soil organic carbon; [3]SOCD = soil organic carbon density; [4]NDVI = Normalized Difference Vegetation Index.

Total carbon content using infrared spectroscopy demonstrated that the mid-infrared results obtained a better correlation with the results of other analytical techniques due to a possible interference from the mineral and particle size fraction of the soil. Some factors such as sample preparation and the number of replicates can interfere with carbon prediction in the soil. Vibrational spectroscopy, such as mid-infrared, can discriminate specific wavelengths and, therefore, different fractions of the SOM (soil organic matter). These methods measure soil reflectance, preserving the original composition of intact soil samples, using dry samples. It can determine both the concentration of soil organic carbon (SOC) and discriminate fractions of this carbon [17,4,9].

The combustion method for measuring total soil carbon (TOC) uses an automatic analyzer to oxidize CO at high temperatures. The organic matter is burned and converted to carbon dioxide, which is analyzed by chromatography and measured in appropriate detectors. The method, in addition to being faster, is more precise and accurate than wet oxidation (Walkey & Black method, for example), as it determines both C in easily oxidizable forms and that present in structures that are difficult to oxidizable. However, it is limited in soils rich in carbonates (inorganic carbon), as it would cause overestimation of organic carbon. Technical limitations such as the need to grind the samples very finely and the use of large quantities of samples (so as to have a soil representativeness), can make with high cost of analysis [18].

The Extreme Gradient Boosting (XGBoost) method is an algorithm used for ensemble learning methods. In the paper analyzed, the method was used to predict vegetation growth over the following ten years, and predicting the growth state and carbon sequestration capacity of vegetation in the area under different climate scenarios. This becomes a quality alternative for managing climate crises and structuring new sustainable routes in the field [13].

Institutions such as FAO (Food and Agriculture Organization), IPCC and EMBRAPA (Brazilian Agricultural Research Corporation), use and recommend direct measurement methods (dry combustion) to quantify soil organic carbon, as they present the use of reagents as an advantage, with low generation of toxic waste. Although this method provides accurate results, it is laborious, and due to the high operational costs of the analysis, its use in most laboratories and by farmers becomes limited. An alternative to direct measurement is the use of obtained isotopes, particularly carbon-13. These techniques can provide more detailed information about the sources and rates of SOC turnover. However, isotopic methods can be complex and require specialized equipment and knowledge [1,9,18,19].

Methods based on infrared spectroscopy, which are non-destructive and clean techniques that use the dry method to quantify SOC, provide the ability to continuously monitor large areas with high resolution, with more economically accessible analysis costs, making them a good alternative for obtain analytical precision and expand quantifications of SOC. However, interpreting remote sensing data can be complex, requiring advanced computational models [9].

Computational modeling methods, on the other hand, use mathematical equations to estimate soil CO_2 sequestration based on parameters. Models can provide continuous data and predict future trends, but model accuracy is highly dependent on the quality of the input data, and may not capture the full complexity of soil processes. Models need to be validated with direct measurements, making the process more complex [9].

The growth of accurate surveys of organic carbon stocks in different land uses and biomes will reduce the barrier to implementing programs that aim to increase SOC on a global scale, making it possible to estimate variations in C stocks and the impact of agricultural development projects and forestry in greenhouse gas emissions and SOC, showing their effects on the carbon balance. This would increase value generation and positive impact on society, together with new sustainability indicators, such as the carbon credit market [9,19].

4. CONCLUSION

Each paper selected in this systematic review contained different methodologies for estimating SOC concentration, which highlights the variability of analytical techniques, which differ in approach and way of expressing results. The main techniques used, replacing the standard method, have been organic carbon analysis by dry combustion, wet oxidation and spectroscopic methods associated with multivariate analysis.

It is concluded that the methodologies used are useful tools for evaluating carbon sequestration in different types of soils through the quantification of SOC; the technological limitations of each method did not restrict the objective evaluation of the work. The strategies used, such as the incorporation of organic matter, the distribution of crops and the use of cover crops, increased the soil's carbon sequestration capacity through sustainable soil and crop management, thus increasing soil carbon reserves. They become a viable strategy for climate change mitigation, serving as a significant reference for future research on carbon storage and for future carbon credits.

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