Agroforestry and its vital role in climate change mitigation in the tropics

Agroforestería y su rol vital en la mitigación del cambio climático en zonas tropicales

A agrossilvicultura e o seu papel vital naatenuação das alterações climáticas nos trópicos

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Abstract

The activities developed by human society cause transformations on the Earth's surface and have the capacity to affect the functioning of the planet. One of the main effects has been climate change, which affects the entirety of the planet, its ecosystems, and society. The objective of this work was to carry out a bibliographic review through the compilation of scientific articles, book chapters, and reviews from reliable documentary sources. The review focused on the factors that influence climate change and its consequences. Additionally, this work presents an alternative: the implementation and use of agroforestry systems to mitigate climate change. This is not only because of their potential to capture and store carbon but also to reduce the amount of CO_2 in the atmosphere through the growth of trees and shrubs. Agroforestry systems also have significant implications for sustainable development due to the social, economic, and environmental benefits they provide.

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Resumen

Las actividades desarrolladas por la sociedad humana ocasionan transformaciones sobre la superficie terrestre y tienen la capacidad de afectar el funcionamiento del planeta, uno de los efectos principales ha sido el cambio climático, que afecta la globalidad del planeta, a sus ecosistemas y a la sociedad. El objetivo del presente trabajo fue realizar una revisión bibliográfica a través de la recopilación de artículos científicos, capítulos de libros y revisiones de fuentes documentales confiables, sobre los factores que inciden en el cambio climático y sus consecuencias, además de presentar como alternativa la implementación y uso de los sistemas agroforestales para mitigar el cambio climático, no solo por el potencial que poseen para capturar y almacenar el carbono si no para disminuir las cantidades de CO_2 de la atmósfera, a través del crecimiento de los árboles y arbustos, también tienen fuertes implicaciones para el desarrollo sostenible debido a los beneficios sociales, económicos y ambientales que prestan.

Palabras clave: uso de árboles, actividad antropogénica, gases de efecto invernadero, captura de carbono

Resumo

As atividadesdes envolvidas pela sociedade humana provocam transformações na superfície terrestre e têm a capacidade de afetar o funcionamento do planeta, um dos principais efeitos tem sido as mudanças climáticas, que afetam a globalidade do planeta, seus ecossistemas e a sociedade. O objetivo deste trabalho foi realizar uma revisão de literatura através da compilação de artigos científicos, capítulos de livros e revisões de fontes documentais confiáveis, sobre os fatores que afetam as mudanças climáticas e suas conseqüências, além de apresentar como alternativa a implantação e utilização de sistemas agroflorestais para mitigar as mudanças climáticas, nãosó pelo potencial que possuem de capturar e armazenar carbono, mas de reduzir as quantidades de CO_2 na atmosfera através do crescimento de árvores e arbustos, também possuem forte simplicações para o desenvolvimento sus sustentável devido à benefícios sociais, econômicos e ambientais que proporcionam.

Palavras-chave: utilização de árvores, atividade antropogénica, gases comefeito de estufa, sequestro de carbono

Introduction

In recent years, the issue of climate change has become increasingly important due to the diversity of phenomena that have occurred, one of the most significant being the global temperature increase. Additionally, the effect of greenhouse gases induced by human activities is causing ocean warming and acidification, melting of sea ice and glaciers, rising sea levels and an increase in extreme weather conditions. There is currently worldwide evidence indicating that climate change is affecting agricultural production due to droughts, rains, floods, hurricanes and other climatic phenomena that affect yields, infrastructure and, in general, productive capacities in agricultural areas (Herrero *et al*., 2015; Babatunde *et al*., 2023). Several factors have a greater or lesser impact on climate change, including the use of fossil fuels, deforestation and agricultural activity. According to Zaar (2021), the increased concentration of CO_2 and other atmospheric gases (CH_4, NO_2, among others) contributing to the greenhouse effect has altered the balance of ecosystems maintained over the past millennia. The Intergovernmental Panel on Climate Change (IPCC), in its March 2023 report, estimates that the trajectory of global warming from now to 2100 is around 3.5 °C. These temperature increases have consequences for the climate and ecosystems, including humidity and precipitation levels. The report also highlights that despite warnings about the effects of climate change on the earth, efforts to reduce greenhouse gas emissions have not been sufficient.

There are several ways to mitigate greenhouse gas emissions globally, one of which is carbon sequestration through the implementation of agroforestry and/or silvopastoral systems, these systems represent an immediately available and relatively low-cost strategy. These well-designed and managed systems can have high carbon (C) accumulation rates, and are presented as an effective tool to mitigate climate change. FAO (2018) has mentioned that with good agricultural practices in silvopastoral systems, their benefits have been demonstrated to not only produce food, but also to generate employment, contribute to food security, and mitigate the effects of climate change.

The objective of this work is to identify the factors that cause climate change and to assess the impact of agroforestry systems on carbon sequestration as a climate change mitigation tool.

Methodology

The article is based on a literature review; the search was mainly focused on information generated in the last 17 years (2006-2023), which were consulted between July and August 2023.

The compilation of scientific articles, book sections and review articles related to the use of agroforestry systems and their effect on climate change in tropical areas was done through reliable documentary sources such as Google Scholar, Redalyc, Scielo and digital repositories such as CATIE (Tropical Agricultural Research and Higher Education Center), FAO (Food and Agriculture Organization of the United Nations), WRI (World Resources Institute) and IPCC (Intergovernmental Panel on Climate Change).

The search fields were first the combination of the keywords agroforestry systems and climate change, and then selected those articles related to the factors that promote climate change, use of agroforestry systems, greenhouse gas production, and carbon sequestration or capture were selected.

Climate change: causes and consequences

Climate change has been defined as “an identifiable and persistent modification of the state of the climate due to natural variability or the effect of human activity” (Hernández, 2020). However, it has been established that climate change is mainly attributed directly or indirectly to human activity, which in some way alters the composition of the atmosphere in addition to the natural climate variability observed over comparable time periods (Gutman, 2009).

Numerous factors have been reported that influence climate change in some way, with the most important ones being the burning of fossil fuels, deforestation and animal production systems.

Fossil fuels

According to McKinsey’s Global Energy Perspective (2019) report, fossil fuels are responsible for 83 % of total CO_2 emissions and coal-fired power generation alone accounts for 36 % of the total. They also note that global energy-related emissions will peak in 2024 and decline by around 20 % by 2050, driven primarily by a decline in coal use in the power sector.

According to Mondragón (2021), the burning and use of energy stored in fossil resources, especially those related to oil, gas and coal, have a drastic impact on the environment, resulting in gaseous emissions during the entire energy production process, gases such as CO_2, CO, SOx, NOx, H_2S, CH_4, among others. However, he mentions that the gas that has the greatest environmental impact is CO_2, due to the large amount produced and its physical properties of radiating the infrared frequency back to Earth, which results in the warming of the oceans and the air near the Earth's surface.

t has been established that one of the effects of climate change due to greenhouse gases is the increase in the Earth's temperature, in recent decades it has increased about 1 °C. In addition, the production of greenhouse gases causes atmospheric pollution, which brings negative consequences on human health (Roca *et al*., 2019).

Deforestation

Forests play a fundamental role in the flow of carbon dioxide from vegetation and soil to the atmosphere (Schlesinger and Bernhardt, 2013), representing a carbon store in both biomass and soil, larger than that of the atmosphere.

Deforestation is a constant loss of vegetation cover due to tree felling, a practice used by man for many years, with the purpose of changing the use of land for other activities such as agriculture, establishment of pastures for livestock, human settlements due to population increase, infrastructure, among others (FAO, 2022). According to data provided by Statista Reseach Department (2023), between 2010 and 2019 in Latin America and the Caribbean, around 53.8 million ha covered by trees and forests have been lost. Table 1 shows the four Latin American countries with the greatest losses of cover.

In the tropics, deforestation caused by agricultural activities not only has effects on soil degradation and loss of productivity, but also contributes a quarter of CO_2 emissions and other gases into the atmosphere. This process causes climatic changes that favor the loss of biodiversity in natural forests and the imbalance of other terrestrial ecosystems (Alonso, 2011).

Table 1. Latin American countries with the highest forest cover losses.

Country	Coverage loss million ha (Period 2010-2019)	Coverage loss million ha (2021)
Brasil	2.50 (only in 2019)	2.90
Bolivia	3.80	0.55
Paraguay	3.60	0.28
Argentina	3.00	0.20

Source: Statista Reseach Deparment (2023).

This practice of deforestation, whether by human action or natural causes (fires, parasites or other factors unrelated to human activity), has consequences on climate change, desertification, atmospheric contamination, soil degradation, food deficit and habitat loss (Cañete *et al*., 2023).

According to Salgado (2014), deforestation can lead to environmental damage; the most severe negative effect is the disappearance of the habitat of millions of species and is a contributing factor to climate change. He also points out that as forests disappear, the emission of greenhouse gases into the atmosphere will increase and the speed and severity of climate change will increase. Similarly, Echeverría *et al*., (2006) report that deforestation affects the hydrological cycle, reducing evapotranspiration and increasing water flow. Effects similar are the case with soil, nutrients, is directly related to anthropogenic forest cover.

In the tropics, the deforestation caused by agricultural activities not only has effects on soil degradation and loss of productivity, but also contributes a quarter of the CO_2 emissions and other gases into the atmosphere. This process causes global climatic changes that favor the loss of biodiversity in natural forests and the imbalance of other terrestrial ecosystems.

Animal production systems

Agriculture worldwide accounts for 25 % of greenhouse gas emissions, including animal production systems whose source of gas emissions is methane (CH_4), which is a by-product of the digestive process of ruminants, where methanogenicarchaea bacteria present in the rumen use CO_2 and H_2, which originate from the microbial fermentation of plant fiber, to form methane and reduce the accumulation of H_2 in the rumen; and their contribution is considered to be about 5 % of the total gases emitted by agricultural activity (Benaouda *et al*., 2017, Soriano-Robles *et al*., 2018). In this sense, Buitriago-Guillén *et al*. (2018), pointed out that anthropogenic practices such as fuel burning and deforestation to increase grazing areas, that is, replacing forests with pastures, have resulted in an increase of greenhouse gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_20), therefore they consider that livestock activities are highly polluting and thatemissions represent one of the factors contributing to current climate events.

In Latin America, the contribution to methane production is 14 %, with Brazil, Mexico, Argentina and Colombia being the countries that contribute most to the emission of this gas, with 44.7, 22.8, 13.7 and 7 %, respectively (Stevens *et al*., 2014).

Research conducted by Zambrano (2022), has shown that animal production systems have a great influence on environmental conditions, through the production of liquid and solid waste (feces, slurry, biological material and by-products), in addition to the release of gases into the atmosphere, the demand for water, the expansion of the agricultural frontier and the reduction of biodiversity.

Another of the agronomic practices in animal production systems that affect climate change is the use of inorganic fertilizers, mainly nitrogenous fertilizers, since they emit nitrous oxide (NO_2) as a result of natural processes, volatilization and runoff, as well as the decomposition of agricultural and animal waste. According to González-Estrada and Camacho (2017), the use of nitrogen in the world in agricultural and livestock activities has grown very rapidly, so it is predicted that the corresponding emissions will increase 50 % by 2030.

Agroforestry systems as a climate change mitigation alternative

Mitigation is nothing more than implementing actions to reduce the emission of greenhouse gases in order to avoid an increase in global temperature. The use of agroforestry systems in its various modalities emerges as an essential strategy in climate change mitigation by capturing and storing atmospheric carbon (León, 2014).

Agroforestry is considered as "a form of land use that includes the use or exploitation of trees of different kinds (timber, fruit, ornamental and plantation) combined with crops and sometimes animals" (Soriano-Robles *et al*., 2018). It is interdisciplinary and the productive land use modality can be a spatial and/or temporal interaction of woody and non-woody plant species, or woody, non-woody and animals. When all are woody species, at least one is managed for permanent agricultural and/or livestock production (Ospina-Ante, 2006).

Cifuentes Jara (2010) has pointed out that climate alterations cause negative effects on agricultural systems, including the length and seasonality of crop cycles, physiological alterations due to exceeding the temperatures to which crops are adapted, water deficiencies and increased erosion due to soil drying and increased surface runoff, and indirectly affect the incidence of pests and diseases, soil cycling and nutrient availability, and increase the propensity to fires.

In this context, agroforestry systems are an alternative within animal production systems, since they can prevent soil degradation, recover soil fertility through the use of leguminous plants and recycle nutrients. Additionally, at a global level, their benefits are centered on carbon sequestration, biodiversity and cultural landscaping.

According to Dolliger and Jose (2019), silvopastoral systems are the key to the transformation from traditional agriculture to climate-smart agriculture that increases productivity in a sustainable and resilient way while reducing or avoiding greenhouse gases.

A large part of the carbon in the atmosphere can be naturally stored by plants in aerial biomass, through photosynthesis processes, and another part in the soil, through the accumulation of organic matter (Contreras-Santos *et al*., 2021), as it is considered the largest carbon reservoir (López-Santiago *et al*., 2019). Trees convert carbon dioxide into plant biomass, storing carbon in tissues such as trunks, branches, leaves and roots (Yirefu Tefera, 2019). Species diversity in agroforestry systems increases photosynthetic efficiency by exploiting complementary ecological niches. Both scattered trees in paddocks, live fences, silvopastoral systems have the potential to sequester carbon far exceeding >19% of what can be fixed by conventional agricultural systems or treeless grasslands (Shi *et al*., 2018).

Carbon sequestration in agroforestry systems

It has been reported that the importance of agroforestry systems in carbon sequestration is centered on two reasons. The first is that the tree component captures atmospheric carbon through photosynthesis, since these trees are perennial plants and store it, behaving as active carbon sinks for long periods of time. The second reason is because agroforestry systems reduce the need to deforest new tropical and temperate forests for migratory agriculture (Clemente-Arenas, 2021).

In this variable, the density of trees in the various production systems directly affects the calculations of carbon sequestered in the form of biomass, both live and in the form of litter on the soil, as well as by the tree species used, the most common being *Leucaena leucocephala, Gliricidia sepium, Sesbania* sp., *Erithrina* sp., *Acacia* sp., *Guazuma ulmifolia*, *Prosopis juliflora*, *Albizia saman*, *Tabebuia rosea*, *Enterolobium cyclocarpum* (Soriano-Robles *et al*., 2018, León *et al*., 2020).

In live fence systems depending on the species, it can be located between 1.7 - 8.9 $t.km^{-1}.yr^{-1}$ and scattered trees in paddocks 1-5 t $C.ha^{-1}$ (Villanueva *et al*., 2018), while, paddocks without trees 4.38 t $C.ha^{-1}$, with low density of trees 7.49 t $C.ha^{-1}$ and with a high density of trees 27.54 t $C.ha^{-1}$ (Melgar-Ramirez *et al*., 2018). Hassán *et al*. (2017) recorded differences between simple (one or two species) and multiple (more than two species) fence types, obtaining values of 3.76 and 5.77 t $C.ha^{-1}$ aerial, respectively.

In a silvopastoral system with 19 years of established *Hyparrehnia rufa* and *Guazuma ulmifolia*, Jiménez *et al*. (2019) reported values in the fractions of tree biomass with 16.46 t $C.ha^{-1}$, forage contribution 1.4 t $C.ha^{-1}$ and 1.9 t $C.ha^{-1}$ in dead material or litter.

Authors such as Contreras-Santos *et al*. (2023), demonstrated in their research that the associations between grasses (*Megathyrsus maximus* cv Sabanera Agrosavia and *Megathyrsus maximus* cv Mombasa) with different dispersed tree species (silvopastoral systems, SSP1 and SSP2, respectively), contained greater accumulated carbon in the aerial biomass (2.18 ± 1.13 and 4.51 ± 3.76 t $C.ha^{-1}$, respectively) than the native grass (*Bothriochloa pertusa* (L.) A. Camus) (0.19 ± 0.09 t $C.ha^{-1}$). The results showed that the silvopastoral systems were able to accumulate atmospheric carbon in aboveground biomass seventeen times more than a traditional production system.

Subterranean carbon sequestration by agroforestry systems

Soil has been considered as one of the resources with the highest susceptibility to climate change, degradation and biodiversity loss (FAO, 2017). Despite this, it has been considered that after the oceans, soils are the largest carbon sinks, significantly offsetting CO_2 emissions (Lefevre *et al*., 2017). Soil also harbors a significant pool of organic carbon. Roots exude organic compounds, promoting the formation of aggregates that retain carbon in the soil. Although it is difficult to quantify soil carbon due to heterogeneity, its long-term stability is essential.

Soil is a large carbon sink with a capacity to sequester between 20 - 26 t $C.ha^{-1}$ at a depth of 20 cm (Benbi and Nisar, 2019, De Stefano and Jacobson, 2017, DíazLezcano *et al*., 2020) with these being higher in tropical and subtropical climates (Hübner *et al*., 2021) with 1/5 of all living soil biomass represented by roots. Hassán *et al*. (2017) reported in single and multiple living fence systems soil organic carbon contents of 39.35 and 37.76 t $C.ha^{-1}$, respectively.

In Research conducted in Colombia by Contreras Santos *et al*. (2020), who compared soil carbon sequestration in different silvopastoral arrangements (pasture + forage shrubs (SSP1), pasture + forage trees (SSP2), pasture + forage shrubs + forage trees (SSP3) and pasture + forage shrubs + forage trees + timber trees (SSP4)) with pasture growing in monoculture. The results indicated that in the silvopastoral systems, soil carbon accumulation ranged from 60.6 (SSP2) to 65.1 (SSP1) $t.ha^{-1}$, while in the monoculture pasture it was 38.3 $t.ha^{-1}$. This indicates that the accumulation of C in silvopastoral systems in the soil increased between 58.2 and 69.9 % with respect to pasture alone. They concluded that the presence of forage trees in livestock systems increases the carbon storage capacity of the soil.

Other research conducted by Contreras Santos *et al*. (2023), comparing two silvopastoral systems with naturalized grass pastures without trees, obtained values of 33.20 and 33.70 t $C.ha^{-1}$ and 24 t $C.ha^{-1}$, respectively, demonstrating that these systems have a high potential to fix atmospheric carbon.

Measurement and quantification of carbon sequestration in agroforestry systems: Advances and challenges

Accurate measurement of carbon stored in agroforestry systems is fundamental to understand their contribution to carbon sequestration. However, this task faces methodological challenges due to the complexity of these systems.

Traditional measurement techniques in agricultural soils often underestimate the carbon stored in agroforestry systems, given the greater organic matter at greater depths. To overcome this, comprehensive approaches combining direct measurements with remote sensing and modeling have been adopted that allow accurate estimation of soil carbon concentration, scaling up data collection to a larger and less invasive scale (Chen *et al*., 2019).

Remote sensing technologies, such as satellite imagery and drones, enable the assessment of spatial and temporal patterns of tree biomass and vegetation, which are fundamental to understanding carbon dynamics in agroforestry systems. These tools not only provide a panoramic view of vegetation distribution, but also generate biomass maps and thus indirect estimates of carbon in aboveground vegetation (Zhang *et al*., 2021).

Simulation models also play a key role in quantifying carbon in agroforestry systems. These models simulate various management, plant composition and land use scenarios, facilitating the assessment of long-term effects on carbon sequestration (Mandal *et al*., 2020). However, these models require accurate and up-to-date empirical data to generate reliable results.

Despite methodological advances, challenges persist in accurately measuring carbon in agroforestry systems (Dold *et al*., 2019). The heterogeneity of these systems makes it difficult to obtain representative samples and extrapolations to larger scales. The lack of methodological standards can lead to inconsistent results across studies, complicating the comparison and synthesis of findings.

Conclusion

There is sufficient scientific evidence that has shown that climate change in recent years has become one of the main problems that society is facing, not only from the environmental point of view, but also the impact on human health, demographics and the economic base of society. The challenge today is to control or reduce greenhouse gas emissions caused by anthropogenic activities, through agreements between governments of developed countries and environmental and social policies.

An important point for this problem is mitigation, and in this sense, the use of agroforestry systems is a viable option, the contribution of these systems can be important when considering their benefits, among which we can mention the sequestration and storage of carbon from the aerial part, soil and roots, and that when well managed can be considered as important carbon sinks and thus reduce the negative impact of gas emissions that affect the environment.

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