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Land Recovery and Soil Management with Agroforestry Systems

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Soils have many ecological functions and provide various ecosystem services including support for global food and fuel production. However, FAO reports indicate that approximately one-third of the planet's arable lands show levels of degradation from processes including soil erosion, low levels of nutrients, acidification, salinization, compaction, sealing, and contamination. These conditions are also found in Brazil where soil degradation is largely caused by inadequate land management. Worldwide, strategic policies have been presented to mitigate this problem, with emphasis on sustainable agriculture. Among them, agroforestry has been identified as a viable system for mitigating and recovering degraded areas. Agroforestry techniques have been developed and tested but are still not understood by farmers, due to their complexity. This study aimed to analyze experiences and studies with agroforestry reported from Australia, some countries in Africa, and Brazil to search for similarities in these complex systems and identify possible correlations to support the hypothesis that land recovery can be enhanced through soil management using agroforestry. A Sankey diagram was developed to illustrate relationships among problems, the adoption of agroforestry and improvements, and the most important contributions. Data analysis shows that the main problems related to soil degradation are soil erosion and decreased soil fertility, while the adoption of agroforestry systems proved to improve different aspects of soil quality and to be a safe path to sustainable agricultural production. To obtain more information on the adoption of these systems in different locations, soils, and climates, it is important to implement policies for reducing land degradation. Furthermore, the assessment of the economic, environmental and social benefits of improving soil fertility and decreasing erosion in agroforestry systems is necessary to validate the use of agroforestry as a sustainable agricultural practice.

Keywords: soil recovery, sustainable development, food security, soil resources, Millennium Development Goals

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INTRODUCTION

Soil is essential for the maintenance of life on the planet, especially for living beings in terrestrial biomes and ecosystems. Among the many functions of soil, its use in food production and for storage and conservation of drinking water are closely related to human life (FAO and ITPS, 2015). One of the objectives of the 2030 Agenda, in relation to the Millennium Challenges established by the United Nations (UN), is to "Protect, recover and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, stop and reverse land degradation, and halt the loss of biodiversity." To achieve this goal by 2030 it is essential "to act against desertification and restore degraded land and soil, including land affected by desertification, droughts, and floods, and to seek for a world neutral in terms of soil degradation" (UNIC Rio, 2016).

Recent FAO reports show that approximately one-third of the planet's arable land is already degraded (FAO, 2022), indicating the urgent need to recover or remedy the damage caused by inappropriate agricultural practices and other factors. Therefore, strategic policies that reinforce the adoption of sustainable agricultural practices are essential to ensure food production and soil conservation. The growth in world population increases demand for food and fuel, impacting productive lands and intensifying the use of current agricultural areas and soil degradation (Hartemink et al., 2008).

The Global Assessment of Soil Degradation (GLASOD) project, which began in the late 1980s, affirmed that soil degradation was caused by "water and wind erosion, loss of nutrients and organic matter, salinization, acidification, pollution, compaction, and physical degradation, waterlogging, and subsidence of organic soils." Similar processes and factors are highlighted by the FAO's Status of the World's Soil Resources report (FAO and ITPS, 2015).

Understanding the environmental problems faced and the means of production are crucial to developing knowledge about food cultivation in biodiverse systems. There are multifunctional indications that agroforestry systems have positive effects in terms of effectively sequestering carbon, enriching soil, conserving biodiversity, and improving air and water quality, which benefit society as a whole (Jose, 2009).

Agroforestry Systems (AFS) are integrated systems involving trees and agricultural and/or animal crops, simultaneously or sequentially, with the objective of sustainably increasing the total productivity of plants and animals per unit of area (Nair, 1985). Another concept that agroforestry comprises land-use systems and technologies in which woody perennial plants (trees, shrubs, palms, or bamboos) and agricultural or animal crops are cultivated on the same plot organized in planned spatial and temporal arrangements (Mosquera-Losada et al., 2012; Nair and Garrity, 2012; Catacutan et al., 2017 apud (FAO and ICRAF, 2019). According to these authors, biodiverse and interactive production systems provide social and ecological benefits. Among them, this study highlights increased soil fertility, control of soil erosion, water regulation, carbon sequestration, biodiversity, and resilience to natural disasters.

Agroforestry has been recognized as a viable system for mitigating land degradation and assisting in its recovery. A range of plant species are used to form a biodiverse agricultural composition in contrast to monocrop systems. In general, agroforestry systems are composed of a diverse mix of trees, crops and herbaceous, and forage species, in which the presence of trees is a requisite. This composition increases biodiversity and local ecosystem services and functions, leading to sustainable rural development, with many environmental and economic benefits. However, farmers may see the planting of trees negatively, due to their occupation of land and reduction of areas for food production (Leakey et al., 2015). Thus, it is necessary to evaluate and consider different forms of local arrangements and compositions of agroforestry systems, which were not compared in this study.

The challenges related to the maintenance and conservation of the environment in relation to its use and exploitation have been discussed for years by the UN Millennium Development Goals (MDGs) and environmental conservations. Garrity (2004) and Leakey et al. (2015) have presented agroforestry options for mitigating environmental problems arising from conventional agriculture systems. Garrity (2004) indicated that the World Agroforestry Center (ICRAF) reported seven relevant aspects in the use of agroforestry to fulfill the MDGs, summarized as improving soil fertility and regenerating degraded lands, reducing poverty in rural areas by growing commercially viable trees, promoting health and nutrition of rural populations, conserving biodiversity, rewarding farmers who conserve watersheds with agroforestry systems, helping farmers access emerging carbon markets, and training people and research institutions in the implementation of agroforestry systems. In their study, Garrity concluded that there is growing use of and research on agroforestry and its environmental benefits in developed countries, and this could have a positive impact in developing countries, citing examples from southern African nations.

Another study that points to the environmental benefits of agroforestry systems involved an analysis of twelve agroforestry farms in Sweden that are recognized as using sustainable agriculture methods. In the cases analyzed, there was recognition that the knowledge and practices adopted by the farmers were sufficient for the development of agroforestry, but it was still seen as a method for enthusiasts. There is a clear need for more research to make the systems profitable, as well as legislative support (Schaffer et al., 2019).

This analysis of agroforestry applications in the southern hemisphere was prompted by the perception that research conducted in different locations would bring similar conclusions about the use of agroforestry and its effects in recovering degraded soils. There is substantial information on the relationship between the application of agroforestry systems and improved soil quality. However, results are different by region and climate, and studies show that the use of agroforestry is more efficient in tropical regions where nutrient cycling is more intense than in cooler regions (Miccolis et al., 2019). This became clear in studies by Rao et al. (1998) in which sub-Saharan Africa provided more conclusive data regarding agroforestry applications than places such as tropical Asia and Latin America.

This study aimed to analyze research about agroforestry experiences as reported from Australia, African countries, and Brazil to identify similarities in these complex systems and possible correlations, to support the hypothesis that the application of agroforestry for soil management can enhance land recovery.

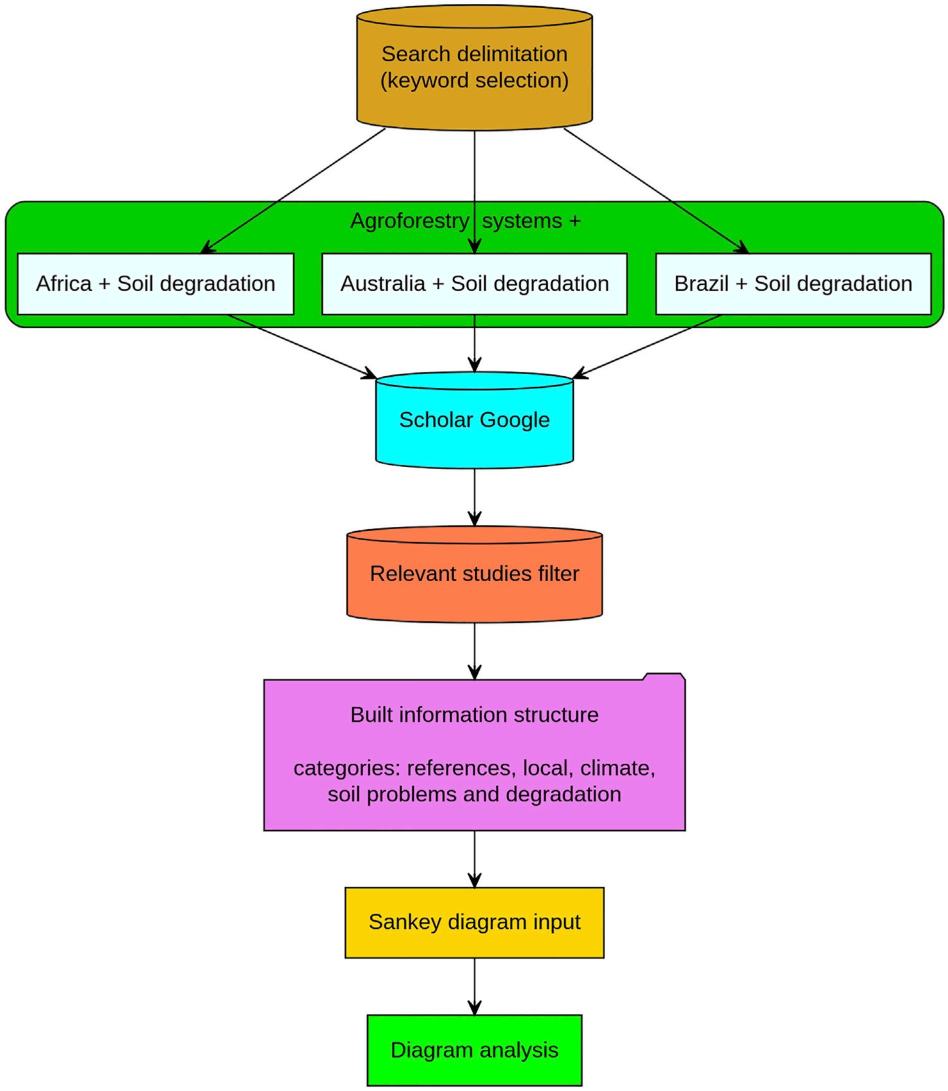

FIGURE 1 | Flowchart of methods applied.

MATERIALS AND METHODS

There is currently debate about ecosystem services and multifunctional agroforestry services, exploring the economic and environmental benefits related to biological, soil, and water conservation. This study focused on information about benefits to soil. The research was carried out using secondary sources to populate a database referring to local land degradation problems identified in the studies and the remediations found from the implementation of agroforestry. These problems and improvements are mentioned in reports by the Millennium Ecosystem Assessment and the International Assessment of Agricultural Science and Technology for Development (Chavan et al., 2016).

This research constructed a database focused on tropical areas. Scientific articles and technical studies were searched in the literature using the keywords: agroforestry, soil degradation, Brazil, Africa, and Australia. We also used the combinations: agroforestry plus soil degradation Brazil; agroforestry plus soil degradation Africa; and, agroforestry plus soil degradation Australia. These searches identified studies about the adoption of agroforestry systems for soil conservation and soil recovery and allowed analysis of the studies. Some studies with data on other locations and climates were maintained in the database for comparison (**Figure 1**).

The first step was to search papers about soil degradation problems and the implementation of agroforestry. Twenty studies were selected that show a strong relationship between soil degradation and the improvements obtained by applying agroforestry systems (**Table 1**). From these documents, information of interest was compiled to analyze possible connections between problems arising from poor soil

TABLE 1 | Relationship between author(s) and local(s).

Author(s)	Local(s)
Cooper et al. (1996)	sub-Saharan Africa
Rao et al. (1998)	sub-Saharan Africa; West Africa; tropical Asia; Latin America; India
Schembergue et al. (2017)	Brazil
Garrity (2004)	sub-Saharan Africa; South Africa; South Asia; China; Australia; Philippines; Brazil; North America; Europe
Jose (2009)	West African; Asia; Americas; Brazil; North America (California, Florida)
Webster (1997)	Africa; Europa; North America
Franzel (1999)	Africa (southern Cameroon, eastern Zambia, western Kenya)
Leakey et al. (2015)	Africa [Cameroon, Nigeria]
Nuberg (1998)	Australia
Baudry et al. (2000)	Europe; Africa; Bolive; Equador; Asia
Amador (2003)	Brazil
Costa et al. (2015)	Brazil
Costa et al. (2013)	Brazil; (São Paulo)
Zomer et al. (2016)	sub-Saharan Africa; South Africa; South Asia; China; Australia; Philippines; Brazil; North America; Europe
Mbow et al. (2014)	Africa
Luedeling et al. (2016)	sub-Saharan Africa; Australia; North America; Brazil; Europe
Schroth (1999)	Brazil (Bahia); South African; East Africa; Australia
De Souza et al. (2020)	Brazil
Kaba et al. (2021)	Africa [Ghana]
Santos et al. (2021)	Brazil

management, agroforestry, and land restoration. The database included data on: location (country and subregion); climate; year and title of the study; problems related to soil degradation; improvements found in the soil (from the application of agroforestry); and the author's main conclusions.

We analyzed the document—The Status of the World's Soil Resources (FAO and ITPS, 2015) using the keywords and subjects described above along with expressions such as: soil erosion by wind and water; organic matter decline; compaction; salinization; and landslides and rock materials. More general qualitative indicators and terms were used to identify problems and/or soil remediation. This study was designed as a qualitative evaluation of practices to restore degraded soils by adopting agroforestry systems.

After the database was compiled, the following rules were used to analyze soil degradation: search category "problems related to soil degradation" using the keywords acidification, compaction, desertification, erosion, fertility, leaching, and salinity; and search with keywords related to "soil improvements" including carbon sequestration, compaction, climate change, erosion, fertility, microclimate, nutrients, organic matter, soil carbon, water.

A Sankey diagram (Kennedy and Sankey, 1898) illustrates the flow of transformation, with the width of the lines representing the flow rate. It has been used to represent land cover and change of land use (Cuba, 2015). In this study it was selected to show the relationship between soil problems, the adoption of agroforestry, soil quality improvements, and relevant contributions.

RESULTS

The Sankey diagram prepared helps to understand the cross-referencing information presented as output, in which the relationships express the links between the "Reference," "Climate," and "Problems," passing through "System (Agroforestry)," and resulting in the "Improvements," as shown in **Figure 2**.

In the Sankey diagram, the width is proportional to the quantity represented, so thicker lines indicate a higher frequency of occurrences. For instance, thicker lines emerging from the authors—"Reference," indicate that the study has more information, which could mean that there were more study locations, or that it presents more problems or improvements. The most common factors in soil degradation are erosion and fertility, followed by losses from nutrient leaching and increased salinity, while desertification and compaction are at a lower level. It is noteworthy that acidification was not presented as a soil degradation factor in the works selected for the study, consequently, it is not in the diagram. One reason may be that most of the weathered soils in tropical regions already have high natural acidity, expressed by low pH values or high aluminum contents. In tropical environments, soils commonly have low levels of nutrients and low pH, leading to aluminum toxicity, and these properties are exacerbated in degraded soils as a result of overgrazing, large-scale mechanized agriculture, and extensive and frequent use of fire as a tool for removal of vegetation and pasture management. Changing land use towards more sustainable practices such as agroforestry can improve soil structure and fertility (Miccolis et al., 2019).

In terms of research that analyzed the effects of agroforestry in the different regions, studies by Rao et al. (1998) and Luedeling et al. (2016) were highlighted in this analysis. These studies are broad reviews of the adoption of agroforestry systems. They do not focus on specific contributions but point out the benefits of agroforestry to soil quality including those observed by farmers.

Problems of soil fertility deterioration and soil erosion were the most cited in the studies included in the database. These problems are related since soil's loss of productive capacity due to low soil fertility increases with the loss of surface soil layers due to

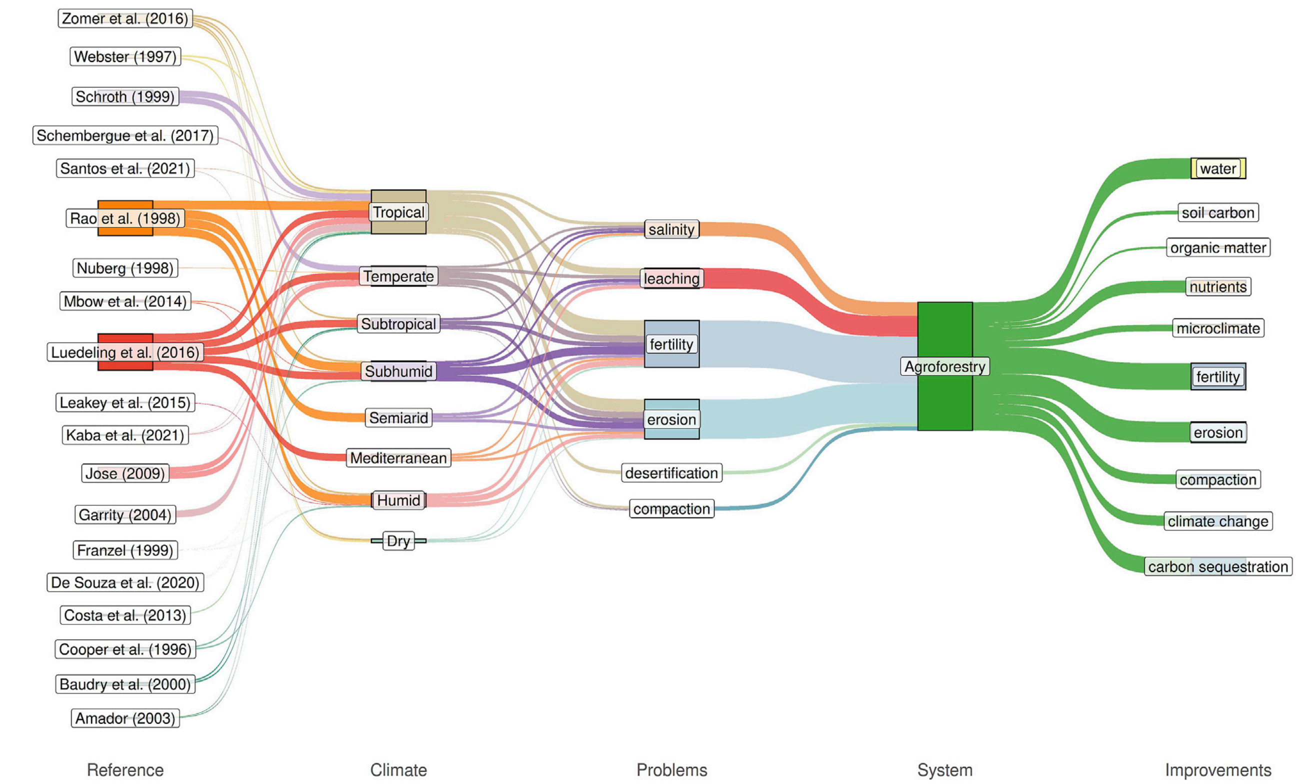

FIGURE 2 | Relationships among soil problems, adoption of agroforestry systems and soil health amelioration expressed in a Sankey diagram.

erosion, both by water and wind, as well as the improper use of tillage machinery. These results corroborate the indication of agroforestry to improve soil quality both in terms of fertility and erosion, as can be seen by the keywords fertility and erosion highlighted (thick lines) in the Sankey diagram. For this parameter of the analysis, the keyword water also stood out, indicating benefits from agroforestry systems including improvements to water infiltration, and reestablishment of the hydrological cycle.

Information on soil problems and improvements in the different studies is mainly from regions with tropical climates, due to the initial selection of countries. However, some of the broader studies on the adoption of agroforestry as a method for soil recovery and conservation have data from other climates, with an emphasis on temperate, subhumid, and humid regions (Feliciano et al., 2018).

The Sankey flow chart can be understood to first evaluate the information with the previously determined keywords (salinity, leaching, fertility, erosion, desertification, and compaction). Then, a search is conducted for these terms in the subsequent column, which indicates the improvements attained by the use of agroforestry. These include benefits such as remediation/mitigation/solutions/improvements to water, soil carbon, organic matter, nutrients, microclimate, fertility, erosion, compaction, climate change, and carbon sequestration. There are many more terms (words) in the process of improvement and transformations of the areas that use agroforestry and these improvements are related to one or more terms (words) from the column of problems. The terms used for problems are commonly cited in the field of soil science. The terms that appear after the use of agroforestry are all taken from the studies examined in this review study.

For instance, water erosion caused by exposed soil is reduced by increasing land coverage with biomass from pruning and plant growth, and recovery of soil structure due to influence from different root systems, which add organic carbon, positively affecting soil biodiversity, nutrient availability, soil fertility, and water retention capacity, etc. Just as the leaching of elements can be reduced by increasing soil organic carbon and improving the use of nutrients by the different plants in the agroforestry system. Soil organic carbon (SOC) storage is determined by the balance between the amount of carbon that enters a system, mainly through the addition of plant residues, and the amount that leaves the soil from mineralization, driven by microbial processes, and leaching out of the soil as dissolved organic carbon. Thus, the amount of SOC is affected negatively by erosion and positively by deposition and transformation of biomass into soil organic matter (FAO and ITPS, 2015).

In terms of locations, the region of Africa with the most weight in this research was sub-Saharan Africa, and, as a consequence of the study design, there is a concentration of works from Brazil and a small number for Australia. A considerable number of studies on this topic are found in North America, and other countries of Latin America, India, Europe, and China, etc.

However, they were not included in the main search, although their data was also addressed in the analysis of the use of agroforestry and its benefits. The list of authors and study locations are seen in **Table 1**.

DISCUSSION

There are many studies on locations with a tropical climate, as seen in **Figure 2**. This may be related to the ease of implementing agroforestry systems in environments with faster nutrient cycling, such as humid tropical regions, and because when designed as a climate change mitigation strategy, these agroforestry systems prove to be efficient for storing carbon in the ground (Feliciano et al., 2018). As analyzed by Cooper et al. (1996) much of the practice of combining trees with crops is based on the natural fallow and regeneration periods of some species in tropical regions of Africa, which led farmers to use them in other regions. This practice became known as enriched fallows, in which certain tree species are planted and maintained to help improve soil fertility. However, the practice is not limited to tropical climates, the use of agroforestry in both subhumid and humid climates is significant in this analysis.

Interactions in tropical agroforestry systems have been analyzed since the 1980s in these regions where hedgerow intercropping (HI) systems or alley cropping involves the growth of crops between hedgerows of regularly pruned tree species. HI systems improved soil fertility, promoted sustainable agriculture on nutrient-poor soils, and helped to control erosion on sloping lands (Rao et al., 1998).

The HI system was a propellant for the application of integrative agroforestry approaches in tropical regions. However, according to Rao et al. (1998), agroforestry is much more complex than annual intercropped systems, due to the unequal arrangement of the components, with dominant and perennial trees, making the systems continuous and not seasonal. Rao et al. (1998) state that tropical agroforestry research has emphasized technologies that utilize the service functions of trees that improve soil fertility and soil conservation. Garrity (2004) also identified the use of integrated agroforestry systems as a differential for small farmers in poor regions with low consumer market infrastructure, as in the tropical home gardens cited by Kumar and Nair 2004 apud Garrity (2004).

Regarding the effects of climate change on production systems, Schembergue et al. (2017) analyzed sites in Brazil to compare agroforestry and monoculture and found favorable conditions for crop adaptations with agroforestry systems, demonstrating that they can be viable alternatives for farmers affected by the negative effects of climate change on their agricultural production. The authors point to changes in both temperature and precipitation at sites that use agroforestry, showing their potential for adapting to changes in climate.

In this analysis, the studies that composed the Sankey diagram did not show significant relevance of agroforestry systems for the term climate change. However, this term is a recent research perspective in soil research and may become more relevant due to recent reports of the Intergovernmental Panel on Climate Change (IPCC). Feliciano et al. (2018) evaluated the benefits of agroforestry to mitigate climate change and concluded that there are not enough regional studies to prove the absorption of greenhouse gases by agroforestry. These gaps about the consequences of climate change can be seen in this study, in which the solutions pointed out by researchers and farmers are more focused on soil quality.

Agriculture production will increasingly need to deal with extreme events of drought and floods and finding means to adapt to climate variations may be crucial for small farmers. In Garrity's research, it is possible to observe two important roles for agroforestry to the Millennium Development Goals (MDGs) (Garrity, 2004). The systems are found to both mitigate the emission of greenhouse gases and allow crops to better adapt to environmental changes.

Other important contributions of agroforestry were analyzed by Jose (2009), Mosquera-Losada et al. (2012), Nair and Garrity (2012), Catacutan et al. (2017), and FAO and ICRAF (2019) who studied issues such as carbon sequestration, soil enrichment, biodiversity conservation, and air and water quality improvement for landowners, farmers and society at large.

Concerning the inherent problems that affect the use and exploitation of soil without conservation practices, higher concentration of information was found about the loss of the productive capacity of the soil, due to reduced soil fertility and increased soil erosion, with these problems being mutually related. This result corroborates those obtained by Tsufac et al. (2021), who concluded that agroforestry systems with different practices improved soil fertility, leading the authors to recommend the use of agroforestry in some activities or as part of productive farms.

Among the biophysical parameters analyzed by Cooper et al. (1996) in their review, they found that declining soil fertility was a serious problem for farmers and that hedgerow intercropping systems somewhat reduced this effect. Farmers in a humid tropical region reported a relationship between certain tree species used in the agricultural systems and increased soil fertility. In relation to soil erosion, Cooper et al. identified problems due to the use of sloping areas for crops and how agroforestry could be applied for soil conservation in these conditions.

Regarding biological diversity Garrity (2004) identified ways in which the adoption of agroforestry systems is beneficial, the first is that "intensification of agroforestry systems can reduce exploitation of nearby or even distant protected areas." As identified by Murniati et al., 2001, Garrity et al., 2003, and Garrity (Garrity, 2004) the "expansion of agroforestry systems can increase biodiversity in working landscapes."

The implementation of agroforestry increases the species and within-species diversity of trees in the farming systems. To summarize, there are positive findings on the use of agroforestry systems for the conservation of natural systems, and adoption of these systems can reduce the need to expand into new areas for agriculture production because previously used land is degraded by erosion and production diminishes due to loss of natural soil fertility.

Agroforestry has been adopted by farmers to restore soil quality, as evidenced by Franzel (1999), with practices such as improved fallow systems in different parts of Africa, which were found to increase the availability of nutrients for the crops. This improved fallowing proved to be an efficient strategy for low-income families. However, Franzel emphasizes the need to investigate why other farms have not adopted this practice and why they have not been recommended by the public sector. According to (Feliciano et al., 2018), there is substantial evidence that improved fallowing increases above-ground carbon sequestration, and together with agroforestry helps to retain carbon in the soil. However, previous studies had inconsistent methodologies and few quantitative analyses and were thus unable to support implementation schemes for farmers and communities.

This study found that low soil fertility is a frequently cited problem and the search for productive systems capable of adapting or mitigating this limitation can help farmers in the regions analyzed. Furthermore, as Nuberg (1998) found in Australia, where the fertility of the soil is low due to intense wind erosion, the use of windbreaks for erosion control improved both problems, although the authors point out that more research is needed on the arboreal species used in these corridors. These efforts were also found in Brazil's Cerrado region, in a study by Miccolis et al. (2019), and the authors concluded that agroforestry promotes soil restoration with non-accounted soil functions and benefits to the environment.

One of the most beneficial factors tree species offer to soil fertility is an increase in living and dead plant biomass. Some studies conclude that the presence of litter prevents the loss of nutrients from erosion due to the direct impact of rainfall on the soil, as verified by Penereiro et al., 2002, Costa et al. (2013) and by Zomer et al. (2016) in different climatic conditions. De Souza et al. (2020) indicated that the management of an agroforestry system with pruning and disposal of green biomass in the soil promotes the recovery of soil chemical fertility faster than natural regeneration. A study on a cocoa farm showed that to improve the decomposition and absorption of nutrients, the enrichment of the ground cover material with biomass from gliricidia trees resulted in a faster rate of decomposition than the use of just cocoa (Kaba et al., 2021). This indicates that there is a need for further studies about which species should be part of an agroforestry arrangement according to the environmental characteristics. However, another study by Cardinael et al. (2018) found no significant difference in carbon stock in the presence of a biodiverse land cover, when compared to an 18-year-old agroforestry system and the control plot. In the same study, it was not clear if the increase in the number of tree species favored an increased stock of organic matter over time.

Thus, in the short term, we can infer that there is a perception of qualitative improvement from the adoption of agroforestry, at least in superficial soil layers; however, this benefit has not been proven in quantitative terms. Nevertheless, Cardinael et al. (2015), Cardinael et al. (2017), Cardinael et al. (2018) showed that there was an increase in soil organic matter in an agroforestry system from the larger amount of biomass added to the system. In agreement with the results found in this study, the increase in fertility perceived by farmers and mentioned in the studies analyzed may be related to an increase in soil organic material in agroforestry systems.

Several studies have identified soil erosion as a critical factor in food production and the conservation of arable land. In a simplified view of agroforestry potential by (Cooper et al., 1996), erosion by water and wind can be reduced with the use of tree species. However, there has been intense debate about the interactions between different species and their root systems. This was analyzed by Schroth (1999) in a review of underground interactions in agroforestry systems, which showed that the development and evolution of plants, in general, have always been associated with competition for space, light, soil, and water resources, and the interactions are not always negative. According to Schroth (1999), some species complement each other or even facilitate a better environment for plant growth, and this can be enhanced with proper management and research on the interactions of different species and their root systems, especially those used in agroforestry. According to Cardinael et al. (2018), a linear model was not efficient for determining the positive or negative interactions between the deeper roots; however, an increase in the availability of organic matter stock between the tree rows was found.

The various studies analyzed here show that the use of tree species brings a differential to agriculture production, but as mentioned by Luedeling et al. (2016), it is important to develop larger and more reliable databases with information on tree performance, for a wide range of agroforestry systems and in different environmental conditions and soil types. The methodology used in this study identified the potential for improving soil conditions, in terms of erosion and fertility, offered by the adoption of agroforestry, highlighting studies that indicate that the use of an agricultural system that integrates crops and tree species can mitigate a widely discussed problem, the loss of soil productive capacity due to decreased soil fertility (Hartemink et al., 2008).

There is, however, evidence that the perception of improved soil quality is not always confirmed by quantitative measures of soil fertility, according to recent studies. Integrated studies may be a new approach to expand research on agroforestry systems in Brazil, where the adoption of agroforestry is associated with the agronomic, socioeconomic, and climatic conditions of the micro-region in which it is applied (Schembergue et al., 2017). This adoption must be accompanied by detailed knowledge of the soil and spatial interactions. According to Schroth (1999), these interactions must be predicted and optimized through proper selection and management of species, and it is already possible to predict quantitative evidence of their benefits with mathematical models (Cardinael et al., 2018).

CONCLUSION

The analysis of secondary sources about the adoption of agroforestry to achieve sustainable food production and reduce land degradation shows that agroforestry can improve soil fertility and reduce wind or water erosion. Agroforestry proved to be important for improving soil quality in several aspects, making this agricultural production system an ally in achieving the MDGs. This analysis found that it is widely recognized that agroforestry qualitatively increases soil fertility and reduces the impact of soil erosion in different regions, but quantitative studies of these benefits are needed since some research has concluded that there are no significant benefits in terms of increased soil organic matter, which is a major indicator of soil fertility.

The volume of sites and research about the use of agroforestry to improve and conserve soil in the tropics may be related to the predominantly low natural fertility of the more weathered soils most common in these regions. Yet, the greater speed in nutrient cycling and plant biomass growth in sub-humid and humid climates facilitates the use of agroforestry systems to mitigate problems of nutrient availability inherent to tropical soils. There is evidence from studies that prove the increase and speed of nutrient cycling from the presence of different species in the same plot, although more studies are needed to be able to widely recommend agroforestry in different regions. The analysis of the different studies allows us to conclude that agroforestry is a safe path to sustainable agricultural production and there was no evidence to the contrary, that is, no study has pointed to a loss or reduction of ecological benefits to the soil.

Regarding the information and knowledge compiled about the benefits of agroforestry, more information is needed on the adoption of these systems in different locations, soils, and climates, which can have great importance to the implementation of policies designed to control soil erosion and increase soil fertility, thereby reducing land degradation. The evaluation of the economic, environmental, and social benefits of increasing soil fertility and decreasing erosion offered by agroforestry systems, under different conditions, is necessary to support public policies aimed at the use of agroforestry as a sustainable agricultural practice. In this sense, we emphasize the need for local studies that point to qualitative improvements and quantitative increments in the arrangements between species for different purposes according to the environment and the needs of farmers.

AUTHOR CONTRIBUTIONS

MM: Conceptualization, search for secondary sources, methodology, writing—original draft, review and editing, visualization. LA: Supervision, review and editing, funding acquisition. AD: Review. All authors have read and agreed to the published version of the manuscript.

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CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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