Soil fertility indicators in crop-livestock-forest integration systems

ABSTRACT

Aiming at agricultural production in a sustainable, satisfactory manner and with less impact on the environment, cultivation systems such as crop-livestock integration, crop-livestock-forest integration, direct planting systems and agroforestry have been adopted. Crop-Livestock-Forest Integration Systems allow the increase in agricultural production without the need to convert new areas to agriculture, increasing the diversification of agricultural production on rural properties and applying different scales of agricultural enterprises. Thus, crop-livestock-forest integration systems are an important alternative for the sustainable expansion of Brazilian agriculture, reducing negative environmental impacts.

Keywords: Sustainable; environmental quality; socioeconomic.

1. INTRODUCTION

In Brazil, one of the main challenges faced by agricultural production is soil degradation [1], which is largely caused by continuous conventional tillage, animal trampling, intense traffic of agricultural machinery and implements, suppression of vegetation cover and lack of pasture management [2] [3]. These factors not only compromise the sustainability of food production but also reduce the soil's ability to effectively maintain essential ecosystem services for human development [4] [5].

According to FAO estimates, the world population should reach around 9 billion people in 2050, directly impacting agriculture, which should increase its production by at least 60% to meet this demand for food. Agriculture thus has the challenge not only of producing more but of ensuring sustainable production in its three axes: economic, environmental, and social, that is, producing more food and less degrading of the available natural resources [6].

In this context, maintaining soil quality, or even obtaining improvements through sustainable production systems, becomes essential to increase food and nutritional security without compromising the balance between the chemical, physical and biological conditions of the soil [7] [8]. In an attempt to seek a balance between agricultural productivity and environmental conservation, in recent decades new agricultural concepts have been developed based on soil conservation, nutrient cycling, and crop diversification [9].

Among these new concepts of sustainable agricultural production, integrated production systems such as crop-livestock integration (iLP), crop-livestock-forest integration (iLPF), direct planting system (PD), and agroforestry (SAFS), have been adopted in replacement of conventional production systems, since, in addition to the numerous benefits they provide to the soil, they increase food production and satisfactorily reduce the negative impact on the environment [10] [9] [11].

The Crop-Livestock-Forest Integration Systems (ILPF) stand out in the so-called sustainable intensification, as they allow the increase in agricultural production without the need to convert new areas for agriculture, based on the diversification of agricultural production within the scope of the property rural, applicable in different scales of agricultural undertakings. It is an approach that benefits from the synergistic effects of its components and that promotes the recovery of the productive capacity of the soil, by producing straw and by covering the soil all year round, avoiding erosion losses, contributing to the improvement of environmental quality and socioeconomic of production [6]. In this way, the ILPF has become one of the sector's main bets for the sustainable expansion of Brazilian agriculture, as it allows for increased productivity with the reduction of negative environmental impacts.

2. GENERAL ASPECTS OF THE CROP-LIVESTOCK-FOREST INTEGRATION SYSTEM – ILPF

The sectoral plan to mitigate climate change for the consolidation of an economy with low carbon emissions in agriculture, better known as the ABC Plan, was implemented through Federal Decree number 7,390/2010 and aims to organize and plan the actions to be carried out for the adoption of sustainable technologies and reduction of greenhouse gas (GHG) emissions by national agriculture [12]. This plan is designed to have a 10-year extension, from 2010 to 2020, and comprises seven core programs:

1) Recovery of degraded pastures;
2) Crop-Livestock-Forest Integration (iLPF) and Agroforestry Systems (SAFS);
3) No-Tillage System (SPD);
4) Biological Nitrogen Fixation (BNF);
5) Planted forests;
6) Treatment of animal waste;
7) Adaptation to climate change.

Integrated agricultural production systems, such as crop-livestock-forestry integration, together with direct planting, were the systems with the highest rate of expansion in recent years. Research carried out in 2015 by the ILPF Network indicates that the total area of integrated production systems in Brazil increased from 1.87 million hectares in 2005 to 11.47 million hectares in 2015 [13].

These field estimates indicate that between the 2015/2016 harvest, there were 11,468,124 hectares in Brazil with integrated agricultural production systems [13]. The last survey took place in 2020 and the total area was 17 million, exceeding the expectations of the Low Carbon Emission Agriculture Plan (ABC Plan), which had estimated a total of approximately 6 million hectares for the year 2020. The region with the greatest implementation of integrated systems is the Midwest, with 40% of the total amount of areas implemented with this type of system.

The forestry livestock farming integration system (ILPF) are sustainable production systems (milk, meat, energy, grains, fiber, and forestry products) that can integrate agricultural, livestock, and forestry activities in the same area, and crops can be intercropped, in succession or rotated. It is an approach that aims at sustainable production, benefiting from the synergistic effects of its components in search of environmental sustainability, and economic and social viability [14] [15].

The idea of ILPF encompasses four strands, and each one has the proper uniqueness for production, as shown below:
1. Agropastoral (ILP), combines the elements of crop and livestock for rotation and practice of consortium or succession, in addition to remaining the activity in the same enclosure for a considerable period;
2. Silvipastoral (IPF), aggregates the livestock and forestry part only in the consortium;
3. Silviagrícola (ILF) transports the forestry and agricultural environment to the extent that there is a consortium of vegetables linked to annual or perennial cultivation and;
4. Agrosilvopastoral (ILPF) which includes the items mentioned above: agricultural, livestock, and forestry, can follow in the rotational environment, consortium or succession, within the same region [16].

These productive systems promote greater stability and sustainability in agricultural production when compared to traditional production systems, with an increase in research related to these systems [17]. There are known positive points in the implementation of these systems, such as productive soil recovery, increased infiltration capacity, and nutrient cycling, re-establishment of the good quality of chemical, physical, and biological soil attributes, improvement of comfort conditions animals, increase in income generation per area, carbon sequestration and mitigation of greenhouse gas emissions and mitigation of the use of pesticides [18]. In addition, there is the possibility of using the cultivation area throughout the year, which contributes to the increase of biodiversity, and reduces the pressure for deforestation, due to income diversification the farmer is less susceptible to market changes [19].

They are still excellent in the recovery of degraded pastures, since with the insertion of integration practices, there is a greater dispersion of residual leaves and branches in periods of drought, which will help to increase the availability of organic matter in the soil, directly influencing the capacity of cation exchange and the presence of nitrogen in the surface zone of the soil as an essential nutrient for plants [12].

3. SOIL FERTILITY

To assess soil quality, indicators can be used in two different and complementary methods: evaluating the variation of the indicator over time within a single system and comparing different systems with each other. Therefore, the definition and delimitation of the indicators need to be essentially related to the management transformation processes. Some physical attributes such as the density and total porosity of the soil, and chemical attributes such as organic carbon content, have been used to assess changes caused by different management practices [20].

Inadequate soil management can lead to losses in its physical and chemical properties, causing the loss of its quality, and ability to maintain biological productivity and sustain environmental quality [21]. The term soil quality does not have an absolute definition, but it can be understood as the capacity of the soil to perform its functions in order to guarantee the growth and development of plants [22] [23]. It is a broad concept, which refers to the balance between the physical, chemical, and biological conditions of the soil, in order to sustain productivity, maintain and increase the quality of the environment, promoting the health of plants, animals, and man [24].

In this sense, quality indicators should be used in order to seek to maintain adequate soil physical and chemical conditions, so that they do not compromise agricultural productivity, adopting resilient and sustainable production systems. However, due to the heterogeneity and dynamics of the soil compartment, its quality cannot be measured directly and can be estimated from quality indicators arbitrated by man, correlating with interventionist practices and its natural composition [25].

Generally, quantitative systems are used with appropriate indicators in the evaluation of soil quality, making comparisons with desirable values in different time intervals, for a specific purpose, in different agroecosystems [26]. For this, it is necessary to use a minimum set of indicators that present characteristics such as ease of evaluation, applicability in different scales, wide use, and sensitivity to management variations [27].

Doran and Parkin [24], were pioneers in soil quality assessment studies and proposed a basic set of physical, chemical, and biological quality indicators, namely: texture, effective soil, and root depth, soil density, soil, infiltration, retention, storage and availability of water in the soil, carbon and total nitrogen contents in the soil, pH, P, K, respiration, and nutrient contents in the microbial biomass.

According to Vezzani and Mielniczuk [28], these indicators were proposed in order to correlate with five soil functions:

1) Ability to regulate and compartmentalize water flow;
2) Ability to compartmentalize the flow of chemical elements;
3) Promote and sustain root development;
4) Maintain suitable biological habitat and ultimately
5) Respond to management by resisting degradation.

4. SOIL QUALITY INDICATORS

4.1 PHYSICAL INDICATORS OF SOIL QUALITY

The physical quality of the soil is determined using indicators that quantify the degree or level of quality. They refer to measurable soil attributes that influence the soil's ability to perform agricultural production or environmental functions, highlighting the attributes most susceptible to alterations by soil management [29]. Soil bulk density (Ds) and porosity are physical attributes recurrently used in the evaluation of soil physical quality. However, it is important to take into account the variation in Ds as a function of soil texture when comparing limiting values. The cited indicators still show high susceptibility to soil management systems, type of agricultural machinery, animal trampling, and environmental conditions of the environment [30].

According to Silva et al. [16], the components of the physical properties of soils, in certain cases, are strong against erosive actions due to the aggregating particles that fulfill the function of sustaining the soil. While for Castaldelli et al. [31], these elements are essential parts of plant nutrition as they promote root growth of species in order to penetrate through the soil profile in order to extract nutrients necessary to supply life, which justifies macroporosity. Finally, the structure of the soil has important physical particularities, which are similar to countless senses of microbial action and organic matter that are excellent indicators of soil productivity [32].

Proper soil management is one of the most important steps in ensuring good soil physical quality, greater sustainability, and maximization of the food production chain. Inadequate pasture management stands out as one of the major causes of the degradation of soil physical quality and causes the formation of compacted layers [33].

The ILPF has been shown to be efficient in the recovery of degraded pasture areas, after the implementation of the Integration Lavoura Pecuária Floresta (ILPF) system, many areas showed improvement in the physical quality of the soil [34]. Costa et al. [35] report that the implementation of SILPF causes a decrease in compaction, influencing an increase in macroporosity and total porosity and a decrease in mechanical resistance to penetration and soil density.

In the case of soil physical properties, its dynamics are strongly influenced by soil texture and mineralogy, which can affect soil resistance and resilience in the face of a given agricultural practice. In this case, changes in physical properties can be evaluated through indicators related to their stability, such as aggregate stability, soil density, total porosity, and mechanical resistance to penetration [36].

One of the most important physical properties to be used in assessing soil quality is total porosity, due to its relationship with microbial activity and CO_2 storage from the atmosphere. A macroporosity value lower than 0.10 $m^3\ m^{-3}$ is quite restrictive for plants, o it compromises the diffusion of gases and reduces the growth of the root system of most crops.

Another physical attribute that has been used as an indicator of soil quality is resistance to penetration (RP), o it is directly related to plant growth [37] and is directly related to soil density, grade compaction, water content, and soil class [38]. For penetration resistance, the critical limit of 2 mPa has been used as an indicator of soil physical quality, both in environments under no-tillage and in areas managed under conventional soil preparation [39].

Soil density, calculated through the ratio between dry soil mass and soil volume, is a good indicator of soil quality, as in addition to indirectly predicting the degree of soil compaction, it can be used to estimate soil density. Soil structure correlates it with the leaching potential, crop productivity, and soil erosive aspects [40].

When talking about soil physical-hydric attributes, water dynamics is used as an important indicator of soil quality, o it is a continuous process that controls the movement of soil chemical elements, soil formation, and evolution, nutrient availability to plants, and satisfaction of water demand by plants [41]. In the study of the dynamics of water in the soil, hydraulic conductivity is generally used as an evaluation variable, and it correlates with several other physical attributes of the soil, such as structure, texture, soil density, particle density, total porosity, macroporosity and microporosity of the soil.

The soil water retention curve (WHC) has been widely used to describe soil water dynamics [42], o it graphically represents the relationship between water retention energy (matrix potential) with its respective content of water [43]. It is an attribute that depends on the intrinsic characteristics of each soil, and results from the joint action of attributes such as texture, structure, mineralogy, and soil organic matter content [44]. It is a valuable soil physical quality indicator, since through it, it is possible to estimate the moisture content at field capacity [45], permanent wilting point, and water capacity available in the soil to plants [46].

The stability of soil aggregates, a process that involves a set of elements such as clay, iron and aluminum oxides, and organic matter as cementing agents in its formation process, is an important indicator of the physical quality of soil, o it restores soil porosity, influencing the water infiltration process and resistance to erosion [47]. It depends on the soil texture and, together with the degree of flocculation and clay dispersed in water, can be used as parameters for evaluating the quality of soils under different management systems [48].

The determination of attributes such as clay dispersed in water and degree of flocculation is important, as these directly reflect on the formation of soil compaction, in addition to influencing the aggregation of soil particles [49]. In this case, the determination of soil texture becomes essential in the study of compaction, formation of aggregates, and credibility, in addition to enabling an indirect estimate of several other factors, among them: water dynamics, soil resistance to traction, and penetration, cation exchange capacity, a dosage of fertilizers and correctives [50].

Another indicator that can be used in the evaluation of the physical quality of the soil is the degree of compaction, o it presents a close relationship with physical soil attributes that are easy to determine, but which are great allies in studies on the influence of different management systems on soil quality., such as soil density, total porosity, aeration capacity and mechanical resistance to penetration [51].

4.2 SOIL QUALITY CHEMICAL INDICATORS

Other attributes can be used as soil quality indicators, in this case, the chemical and biological ones, as they are involved in the measurement of nutrient release processes, mainly organic matter into the soil [7]. The evaluation of chemical and biological indicators of soil quality is very useful for defining the quantities and types of fertilizers required by plants and maintaining or recovering productivity, especially in tropical soils, where exposure to climatic factors such as rain and sun, make poor nutrients, with high acidity and water deficit [52].

Soil chemical attributes directly influence soil productivity, pH, for example, plays a fundamental role in productivity, which is to control the solubility of nutrients in the soil and consequently influences the absorption of these nutrients by plants [53]. Some attributes that can be used to identify soil fertility are pH, organic matter, phosphorus, calcium, magnesium, potassium, sodium, hydrogen plus aluminum, the sum of bases, cation exchange capacity, and base saturation [23].

Soil organic matter (SOM) is considered by many scholars as the ideal indicator for assessing soil quality, o it is very effective in determining the quality of soils altered by management systems [54]. Soil organic matter (SOM) comprises all organic material contained in the soil, ie leaf litter, microbial biomass, water-soluble organic substances, and humus (stabilized organic matter). By determining the SOM, it is possible to determine the appropriate management that contributes to the sustainability of natural resources and the environment [55].

Studies indicate that the use of integration systems leads to improvements in soil quality. The positive results have been attributed to the nutrient cycling process resulting from the presence of animals in the system, which accelerates the nutrient cycling process by making them available in mineralized form through feces and urine [17]. Pasture systems associated with annual crops to produce grains are more efficient in conserving soil fertility, favoring plant growth, since species with root systems of different morphologies provide greater nutrient cycling [56].

Oliveira et al. [18] state that inefficient soil management impairs the quality of nutrients dispersed for its fertility in SILFP, analyzed in the municipality of São Domingos do Araguaia - PA. [57] concluded that, after research in Santa Fé – PA, the percentage of organic carbon favored the elevation of microbiological processes and a greater probability of absorbing subsidies to plants in ILPF systems, which provides improvements in soil chemical attributes.

Soil quality chemical indicators are of great relevance in agronomic and environmental studies and are usually divided into four groups:

1) Those that indicate soil processes or behavior, such as pH and Organic Carbon;
2) Those that indicate the capacity of the soil to resist cation exchanges, such as: type of clay (1:1 or 2:1), CTC, CTA, iron oxides, and aluminum oxides;
3) Those that indicate the nutritional needs of plants: macro and micronutrients;
4) Those that indicate contamination or pollution: heavy metals, nitrate, phosphates, and pesticides [58] [59].

4.3 BIOLOGICAL INDICATORS OF SOIL QUALITY

Soil organic matter has commonly been used as an indicator of soil quality, due to its susceptibility to alteration in relation to soil management practices and because it correlates with most soil properties. SOM is an important component of the soil and refers to all organic material present in the soil including litter, light fraction, microbial biomass, water-soluble organic substances, and stabilized organic matter, better known as humus [60].

Therefore, determining the content of organic matter in the soil and its constituents becomes an indispensable tool for assessing soil quality, especially for tropical ones, since they are highly weathered and organic matter favors the retention and availability of water, in addition, to acts in the release of nutrients for plants [61]. For Nanzer et al. [62], among the soil quality indicators related to soil organic matter, the carbon stock is one of the most reliable, because depending on the management system adopted, its contents can remain stable, increase or decrease, in relation to the areas where there is no anthropic interference.

It is related to the amount of organic matter in the soil, the rates of decomposition of this matter and the root activity of plants [63]. In forest areas, the carbon stock tends to be greater in surface area due to the greater deposition of organic material, mainly leaves and branches [64], while in forest areas with a predominance of savannah species, there is an allocation of biomass to the roots, increasing the carbon stock in the deeper layers of the soil [65].

Changes in Total Organic Carbon (TOC) contents are difficult to detect in the short term, partly due to the high natural variability of soils, however, its determination in production systems over time is essential, o it may allow measuring the degree preservation of natural ecosystems and the possible impacts caused in agricultural systems with different types of soil management [9].

The study of soil carbon modifications caused by land use change makes it possible to adopt management measures that reduce the risks of future negative impacts on the soil [7]. Generally, when forest soils are converted to pasture or agriculture areas, a drastic reduction in soil organic carbon content is observed [66], mainly in the top twenty centimeters of the soil profile [67], a consequence of inadequate soil management, through tilling or even lack of maintenance of the soil cover. There is a strong interaction between organic carbon and soil physical attributes with management activities, assuming then that the evaluation of this variable (TOC) is important in the process of choosing the most appropriate soil management practices, which can make agriculture a more socially and environmentally correct activity, and to act in the mitigation of greenhouse gas emissions into the atmosphere, in order to reduce the pressure for opening new production frontiers [68].

According to Assmann et al. [69], increases in soil organic carbon stocks are influenced by a combination of factors that affect the soil-plant-animal-atmosphere relationship. Climatic conditions, such as rainfall and rainfall distribution, as well as soil type, quantity, and quality of plant and animal residues added to the soil, influence the dynamics of organic matter. According to Loss et al. [70], practices such as soil turning promote the breakdown of aggregates and consequent exposure of organic matter, favoring its mineralization and reduction. Oliveira et al. [71] highlighted the non-mobilization of the soil, the continuous contribution of biomass, the permanent presence of soil cover, and the replacement of nutrients as fundamental practices for maintaining and/or increasing the levels of organic matter in the soil. Assmann et al. [69] also reported that the frequency and method of grazing (rotated or continuous) alter the dynamics of soil organic matter.

5. EFFECTS OF ADOPTING INTEGRATED AGRICULTURAL PRODUCTION SYSTEMS ON THE PHYSICAL, CHEMICAL AND BIOLOGICAL IMPROVEMENT OF SOILS

Currently, several studies have been carried out with the aim of identifying management systems that promote an increase in soil quality [72]. Integrated agricultural production systems seek to increase SOM and promote improvements in the physical, chemical, and biological properties of the soil, enabling an increase in productivity and a reduction in expenses with irrigation, fertilizers, soil conditioners, and other agricultural inputs [73].

The integrated production systems work to increase and maintain the levels of organic matter, which favor the complexation of toxic elements, the ability to exchange cations, such as cementing agents in the soil structure, and buffering power over the pH [74]. Despite some questions about the possible negative effects that integration systems can promote on the soil over time, such as soil compaction and increased density, authors such as Souza et al. [75], and Vilela et al. [76] observed an increase in phytomass, a decrease in nutrient leaching and an increase in soil microbial biomass in consolidated integration systems.

The vegetation cover maintained on the soil surface reduces the negative impacts caused by mechanical compression, whether caused by animal trampling or by the inappropriate use of agricultural machinery and implements. Studies prove that the mechanical compression applied to the soil causes less physical damage, when it has considerable levels of coverage (green or dry), as observed by Moreira et al. [77]. They found that, after eight years of implementation of the iLPF system, animal trampling did not change the aeration porosity and soil permeability to air in relation to the area without grazing.

With regard to fertility, improvements in phosphorus availability are observed in production systems that adopt crop-livestock-forest integration, due to the maintenance of permanent cover on the soil, which acts on its adsorption through the release of organic anions that compete for the same absorption sites [78].

ILPF systems can promote increases in soil organic matter content under different edaphoclimatic conditions. In this context, positive results regarding the quantity and quality of soil organic matter were observed in integrated production systems [69] [70] [79] [73] [80] [71].

Despite the results at the level of Brazil, much remains to be done when it comes to integrated production systems, especially with regard to the advancement of knowledge and technology transfer, as they present high complexity, diversity, and synergy between components [81].

Silva et al. [57] studied the physical attributes and availability of soil carbon in Integrated Crop-Livestock-Forest (ILPF), Homogeneous, and Santa Fé systems, in the state of Pará (Brazil) and found that eucalyptus rows in the iLPF system and Santa Fé improved the soil density and porosity conditions, as well as the accumulation of organic carbon. These results for the physical attributes are explained by the fact that Brachiaria ruziziensis forage was introduced in the iLPF (iLPF2.5 and iLPF10) and SSF systems as a cover plant, with the formation of organic matter, which improves the soil structure, o it helps in cementation and stabilization of soil particles, in addition to mitigating the negative impact of animal trampling and uniformly distributing the weight of agricultural machinery and implements.

Coser et al. [80] when assessing short-term carbon accumulation from a low-productivity pasture to an agroforestry system in the Brazilian savannah. These authors found that both stocks and C accumulation rates increased with the adoption of the integrated production system and that the carbon management index (CMI) increased mainly in the 0.00-0.10 m layer, showing the ability of the agricultural system to raise the labile organic matter and reach the same MIC as the reference area (native cerrado).

It is known that the conservation management practices that make up these systems promote the long-term construction of soil fertility, which provides an improvement in physical, chemical, and microbiota attributes. This fact is evidenced in the numerous works that show consolidated results through the adoption of these systems.

4. CONCLUSION

Integrated production systems promote greater stability and sustainability in agricultural production through productive soil recovery, increased infiltration capacity, and nutrient cycling, reestablishment of good quality soil chemical, physical and biological attributes, improved comfort conditions for animals, increase in income generation per area, carbon sequestration and mitigation of greenhouse gas emissions and mitigation of the use of pesticides.

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