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Systemic Soil Fertility as product of system self-organization resulting from management

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ABSTRACT: Soil Fertility is one of the most relevant fields of Soil Science related to agricultural production, especially in tropical and subtropical environments, due to the prevalence of weathered and naturally unproductive soils. However, indicators of Soil Fertility currently used do not represent what actual happens in the soil; once must be understood as a process. The wisdom of this importance occurred in Antiquity and evolved until the mid-19th century, when the *mineralist concept* was proposed, which is still dominant in Brazil and worldwide. In this process, Soil Fertility has been associated with current perceptions, soil chemical properties and management systems in the development of agriculture over time. During the evolution of Brazilian agriculture, from the 1960's onwards and most notable with the consolidation of conservation management in the 1990's, *Intrinsic limitations* were increasingly evident on the ability of indicators to assess the actual level of Soil Fertility and the respective response of the plants. Concurrently, the view of the soil as an open system was strengthened, and the conception of fertility began to constitute a property that emerges from the functioning of the soil, whose processes are self-organizing, due to the continuous flows of energy and matter driven by organic compounds. In this context, we present a part of the history of Brazilian agriculture, relating it to its management and *Intrinsic limitations* of indicators to assess Soil Fertility due to changes in soil functioning. The *Intrinsic limitations* added to understanding based on a systemic approach of the functional processes of the soil are the practical and theoretical bases for the proposition of another concept: *Systemic Soil Fertility*.

Keywords: agriculture history, mineralist concept, fertility assessment limitation, soil evolution, soil resilience.

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INTRODUCTION

Fertility is a broad term related to abundance, success, capacity, wealth and reproduction. Thousands of years ago, the wisdom of *good land* led to the notion of *fertile land*, which allowed human survival and the growth of humanity through the production of food and coexistence within communities. Over time, as knowledge accumulated, various perceptions and theories were proposed until the *mineralist conception* presented by Liebig in 1842 (Egerton, 2012). This concept survives until the current days and has the restitution of nutrients exported by plants as the main rule, which is the rationale for contemporary fertilization.

Implantation of high productive agriculture on a large scale in Brazil through the use of conventional soil tillage, from the 1960's onwards, led to the intense degradation of arable land. This situation gave rise to the need to adopt conservatist land management techniques. Where this type of management was employed, gains in organic material as crop residues and an increase in soil organic matter were observed. Thus, the continuous flow of energy and matter that permeates these production systems, which is driven by organic compounds, has raised agroecosystems to another functional level.

Greater magnitude of the flow of energy and matter and their longer soil permanence generates new forms of organization between the components in a self-organizing process, which progresses to the emergence of more complex structures with a higher number of inter-relationships. At each state of organization, new properties emerge, which can perform more functions than the previous state. The components of the system are in a continuous dynamic reorganizational process; thus, fertility assessment procedures enshrined in the mineralist conception do not allow the understanding of the actual Soil Fertility as there is no capacity to detect in a similar way to the plant perception. In this process, as the soil system evolves, *Intrinsic limitations* of indicators to assess Soil Fertility appear, which complicate the characterization of the existing relationship between abiotic factors, the soil, edaphic organisms and plants.

The evolution of the Soil Fertility concept has always been linked to the dominant paradigm of chemical properties associated with the agricultural management system, but clearly these indicators do not reflect the actual situation in the soil. The purpose of this paper is to present evidence that the current concept does not reflect the reality observed in agricultural production systems under conservational management and that there are practical and theoretical bases for the proposal of another concept of Soil Fertility.

EVOLUTION OF THE SOIL FERTILITY CONCEPT

The first notion about Soil Fertility was formulated even in Antiquity, more than 8,000 years BC (Blayney, 2008) when humans began to explore and cultivate wild cereals and domesticate animals, which allowed them to live in communities. From that period onwards, the evolution of agriculture occurred predominantly in river valleys, as the concept of *fertile land* was also associated with water availability. In these places, the soil was kept fertile by periodic flooding. Thus, the evolution of agriculture and civilizations became inseparable from the concept and understanding of Soil Fertility.

A second concept of Soil Fertility was probably enunciated by Collumela in 42 AD (Nicolodi and Gianello, 2016), who synthesized and improved the knowledge built in Antiquity, interpreting the concept of Soil Fertility *as the continuous and renewable capacity of cultivation*. In the 12th century, the Arab-Islamic contribution to this concept was proposed by Ibn Al Awan whose was the first to relate *the action of weathering to the availability of food for plants* (Lopes and Guilherme, 2007). For a long period, including the Middle

Ages to Contemporary times, the understanding of *nutriment*, a generic name to refer to the food that plants took from the earth, predominated.

Human interest in Soil Fertility was driven by the need to obtain food to survive and the aim of prospering with the profit gained from the commercialization of agricultural products. In this perspective, they started cultivation and endeavored to provide the soil with adequate conditions for greater and better food production. Thus, from the 18th century onwards, people began to investigate the vital food for plants instead of nutriment. For Wallerius, in 1761, it was the soil humus, constituting the *humist theory* (Egerton, 2012).

However, the greatest advance in the understanding and conceptualization of Soil Fertility was the *mineralist conception*, proposed by Liebig, in 1842 (Egerton, 2012), which has persisted until the present day. This conception was based on two statements established by De Saussure, in 1804 (Egerton, 2012), in postulates of extraordinary scientific importance: 1) the food of plants is the soluble salts released by the humus, and 2) the need to return to the soil the elements exported by crops (Nicolodi, 2007). In essence, the *mineralist* conception differed from the *humist* one, in advocating that the soluble nutrients were the plant food and not humus; however, both considered Soil Fertility as the nutriment of plants, characterizing the *humo-mineralist* concept.

These postulates served as the basis for the development of modern Agronomy and promoted the greatest progress made in agriculture from the perspective of knowledge about the soil. From 1842, Soil Fertility began to be measured because, during this period, the development of laboratory equipments and methodologies were intensified, allowing the chemical analysis of soil, plants, and fertilizers.

Liebig's postulates promoted advances in the understanding of Soil Fertility worldwide in the subsequent 180 years, and more specifically in Brazil, over the last 60 years. According to Nicolodi (2007), probably the first published definition of soil fertility in this country was proposed by Catani et al. (1995), who described it as *the capacity of the soil to provide nutrients, water and air in sufficient quantities for crop development, within the limitations imposed by climate and other biotic and abiotic factors*. It is a more comprehensive definition of that presented by Liebig and that defined by the Brazilian Society of Soil Science (Curi et al., 1993), which refers to *the state of a soil with respect to its capacity to supply the essential elements for plant development*. Alternative definitions such as Tisdale et al. (1993) and those by Brazilian authors (Bissani et al., 2004; Sousa and Lobato, 2004; Cantarutti et al., 2007; Lopes and Guilherme, 2007; van Raij, 2011), refer to *the capacity of the soil to supply plants with nutrients in adequate amounts and proportions necessary for their development and to maintain the absence of toxic elements*.

Even though there have been advances in the evolution of the concept of Soil Fertility in Brazil during this period, the most important one was the *chemical-mineralist* concept, in which the term *chemical* refers to methodologies and to equipments for the analysis of soil chemical properties and the *mineralist* term that is related to the availability of nutrients for plants.

Fragmentation of Soil Science into themes being studied in isolation, using a reductionist approach, contributed to the way in which Soil Fertility was consolidated in the context of agriculture. Thus, it is possible to define the *Natural Fertility*, resulting from the soil formation process, in the function of the relationship between the source material and the environmental conditions. The *Actual Fertility*, as that resulting from the soil management practices under cultivation. The *Potential Fertility*, as that which fully meets the requirements implicit in the restricted concept of fertility and which manifests itself in the most favourable conditions in relation to biotic and abiotic factors. From a reductionist perspective, *fertile soil* is considered to contain all the essential nutrients in sufficient and balanced amounts in assimilable forms and free of toxic elements required for agricultural production. And a *productive soil*, also from a reductionist perspective, is the fertile soil inserted in a context of adequate biotic and abiotic conditions. From this, it is concluded that *fertile soil is not necessarily a productive soil, but all productive soils are fertile soils* (Camargos, 2005).

AGRICULTURAL EVOLUTION AND SOIL MANAGEMENT IN BRAZIL

After the arrival of the European settlers, the history of the agriculture developed from their management practices can be divided into two major periods: the first, between 1500, the year of Discovery of Brazil, until the 1960's; and the second, from the 1970's onwards (Dossa, 2004). In the second period, new concepts and new technologies emerged in rural areas, especially those related to the modernization of agriculture and the *Green Revolution*, leading to a new level of productivity through the specialization of the productive units (Anghinoni et al., 2018).

This development brought great advances in agricultural production in Brazil, especially in *commodities*. Agricultural mechanization associated with the intensive use of modern inputs, such as mineral fertilizers and agrochemicals, and government policies with facilitated financing to recover degraded areas in the south of the country and to explore new large areas in the Cerrado region, promoted these advances (Sá, 1993, 1999; Ruedell, 1995; Wiethölter, 2000; Lopes et al., 2004; Camargo, 2015).

Intensive use of conventional soil management systems, designed for use under a temperate climate, which were used both in agricultural production and in extensive cattle raising, accelerated the degradation process when applied in Brazil (Muzzili, 2002). Even though large gains in productivity have been obtained, this type of soil management combined with intense rainfall and the burning of residual crop biomass has reduced the efficiency of the use of the applied inputs. This is certainly due to the degradation of the structure and functionality of the soil. Thus, despite the increase in agricultural production, the primary objective of the technological innovations of the *Green Revolution* was not achieved.

From the 1970's onwards, with indicators suggesting the negative impact of the current agricultural practices on the soil and the environment, the adoption of more *conservationist soil management* in Brazil began to be advocated. Initially, with the use of the *minimum tillage* and, later, the *no-tillage* systems. However, it was only towards the end of the 1990's that the agricultural area using conservation management systems began to grow exponentially. Currently, it is estimated that more than 36 million hectares are cultivated under these systems (Febrapdp, 2021), placing Brazil at the top of the rankings of the area cultivated in countries with tropical and subtropical climates and in global terms, surpassed only by the USA.

More recently, at the beginning of the 21st century, the integrated agricultural production systems reappeared in Brazil (Carvalho et al., 2014; Moraes et al., 2018) under the pillar of conservation management, especially in the no-tillage system. These are productive systems using associations between crops and animal production to explore synergisms arising from the interactions between soil, plant, animal and atmosphere, known as integrated crop-livestock systems (ICLS) (Carvalho et al., 2014; Moraes et al., 2014). In fact, this is not a new technology, as its precepts have long been in use around the world, but they had been neglected with respect to specialized production systems resulting from the *Green Revolution* (Carvalho et al., 2015). However, the concept of integration has recently regained strength in Brazil and worldwide due to the inefficiency of current agricultural and livestock production models. In this context, ICLS has been recognized as a singular option for a production system, in which it is possible to aim for intensification and sustainability simultaneously.

Successional agroforestry is another diversified production system that has been expanding in Brazil in recent decades. Successional agroforestry systems (SAFS) are combinations of the arboreal element with herbaceous plants and/or animals, organized in space and/or time characterized by the high diversity of species and the vertical occupation of different strata. The care in managing the incidence of solar radiation on vegetation, primary productivity, ecological succession, nutrient cycling and the relationships between productive components and environmental factors are particularities of SAFS (Steenbock and Vezzani, 2013).

EVOLUTION OF SOIL PROPERTIES WITH MANAGEMENT

Conventional tillage: the beginning of the development of Brazilian Agriculture

The period of greatest developments in agricultural production in Brazil began in the late 1960's. From that time onwards, studies were conducted to select chemical methods for soil analysis and a network of calibration experiments was implemented for different soils, climate, crops and management conditions throughout the country, following the premises of the *chemical-mineralist* concept of Soil Fertility (Cantarutti et al., 2007). From the beginning of the 1970's, the use of these analyses to indicate the necessity for liming and fertilization programs quickly spread. In 10 years, it surpassed the mark of 3.3 million samples analyzed, with around 400 thousand in 1981 alone (Cabala-Rosand and van Raij, 1983). The programs made it possible to obtain information about the response of crops to liming and fertilization and their productive potential. This information enabled the establishment of large-scale agriculture in acidic soils with low nutrient availability, widespread in Brazil, which were previously considered unsuitable for agriculture.

Despite promoting important increases in crop productivity, Soil Fertility was not significantly improved by applying fertilizers and acidity correctors, probably due to soil degradation and nutrient losses that are consequences of intensive soil tillage. Significant benefits only began to appear with the use of conservation management, initially through minimal tillage and, later, no-tillage systems (Nicolodi et al., 2014).

Minimal tillage: transition phase

Minimum tillage and subsequent seeding are characterized by less soil mobilization (harrowing, superficial subsoiling or scarification), reduction and/or no residue burning, cover crop cultivation in the off-season resulting in greater ground cover. The adoption of these practices lasted, as the dominant management, for a short period in the 1980's/90's, which marked the beginning of the process of the recovery of soils with physical degradation, as indicated by physical properties and water erosion indicators, resulting from the decrease in mechanical action when compared to conventional tillage. With this new management system, there was a reduction in organic matter loss and even gains in some cases due to the remaining straw from the crops with a positive effect on soil reaggregation. However, even with these notable improvements, the negative residual effects of the previously intensive soil tillage remained, as part or all of the topsoil had been lost by water erosion.

No-tillage: the consolidation of conservation management

Given the intense process of soil degradation, the first experiences with no-tillage emerged in the South of Brazil in the 1970's, both as research and as a production system, which today occupies 49.6 % of the areas destined for farming in Brazil (Embrapa Territorial, 2020; Febrapdp, 2021). Conceptually, the no-tillage system (NTS) encompasses an ordered complex of interrelated and interdependent agricultural practices, which include, in addition to no soil perturbation, crop rotation and the use of cover crops (Muzzili, 2000) or grazing (Moraes et al., 2018) to form and maintain plant ground cover. When some of these crop management requirements are not fulfilled, it is only considered no-tillage, with the same meaning as direct-sowing or direct-seeding.

From the 1980s onwards, long-term experiments were implemented to detect small changes in soil properties within a complex matrix of factors. Transdisciplinary scientific research provided an opportunity to quantify the effects of management on soil properties (Anghinoni et al., 2017). This approach focused on studying the dynamics of soil organic matter and its fertility, in two aspects: using the concept restricted to the quantification of chemical attributes; and in a broader concept that included the soil-plant relationship.

Many changes in soil properties in the NTS were verified over time, predominantly due to the accumulation and quality of the crop residues. This resulted in the reestablishment of the microbial biomass and the reaggregation of the soil, building a structure with a better capacity to retain nutrients and water; the shift from immobilization to nitrogen availability; the increase in organic carbon and phosphorus (Sá, 2001; Mielniczuk et al., 2003); the decrease in the effects of soil acidity (Salet et al., 1999; Alleoni et al., 2010; Martins et al., 2014), with an increase in the cation exchange capacity and nutrient cycling (Sá, 1999; Assmann et al., 2015, 2017).

As NTS was consolidated, plant species options emerged to increase crop diversity and aggregate their benefits of biological relationships in soil fertility (Lopes et al., 2013; Mendes et al., 2018). Biological indicators, such as microbial biomass and basal respiration, and biochemical indicators, such as enzymatic activity, started to be evaluated. There emerged close correlations between these indicators and the organic matter content of the soil and the availability of nutrients, showing the importance of biology in the functioning of NTS (Chaer and Tótola, 2007).

From this perspective, Mendes et al. (2018) proposed the Soil Ferti-Biological Quality Index ($SQI_{FERTBIO}$) that associates soil chemical indicators with biological indicators in a routine analysis: available nutrient content, acidity measures, cation exchange capacity, organic matter content (available reserve of nutrients) and enzyme activity, as a measure of the contribution of nutrient cycling. The use of $SQI_{FERTBIO}$ in consolidated NTS in the Brazilian Cerrado soils has allowed the verification that crop productivity had no significant relationship with soil chemical indicators (Mendes et al., 2019), opposing the *chemical-mineralist* concept, but this relationship increased when biological indicators were considered. Therefore, in the long-term, conservation management systems have demonstrated that the simple assessment of chemical properties by soil analysis does not reflect the soil fertility perceived by plants.

Integrated production systems in no-tillage: the path to sustainability

The resurgence of integrated agricultural production systems in Brazil is due to the search for diversity in production systems because of the benefits identified in the soil properties. The construction of integrated crop-livestock systems (ICLS) starts with the choice of their components, the strategy of their spatiotemporal arrangements between soil-plant-animal-atmosphere components and the integration of multifunctional agricultural activities (grains, pasture, animal production and wood) (Moraes et al., 2014), which define the nature of the elements involved and the number and magnitude of the flows that constitute the biogeochemical cycles (Anghinoni et al., 2013).

The novelty and relevance of ICLS in soil conservation management lies in the synergism generated by systemic processes provided by animals' presence, which, when grazing, are catalytic agents, recycling organic material and determining the dynamics of nutrients between nutrients soil-plant-animal-atmosphere compartments. Nutrient cycling is certainly one of the most significant benefits of animals during the grazing stage. Thus, under grazing, the nutrients absorbed and incorporated into the plant biomass are consumed by the animal, but there is a low level of incorporation into the animal tissues (Haynes and Williams, 1993). The remainder returns to the soil as pasture residue and animal excreta. Decomposition of pasture residues and excreta are added to those released during commercial crop production, in succession or rotation with the pasture phase. These nutrients are released into the soil solution, incorporated into microbial biomass and soil organic matter (Anghinoni et al., 2015, 2018). The amount of nutrients released in the grazing phase is similar to that when commercial fertilizers are applied to the crops, since the animal works as a recycler *par excellence* (Anghinoni et al., 2011; Assmann et al., 2015, 2017). The effects of animal presence on acidity properties manifest as the greater and faster action of the lime applied to the soil surface in reaching the deeper soil layers, verified by the pH, base saturation and aluminium levels (Flores et al., 2008; Martins et al., 2014).

In successional agroforestry systems (SAFS), the greater addition of diversified plant material through pruning the vegetation, deposited onto the soil surface, is the key feature. This is because plant biomass catalyzes the ecological processes that ensure the self-regulation and sustainability of the system (Steenbock and Vezzani, 2013) and has a positive impact on the biological, physical and chemical properties of the soil (Cezar et al., 2015; Froufe et al., 2019), resulting in high productivity in lands normally characterized by low natural fertility.

INTRINSIC LIMITATIONS IN THE CHARACTERIZATION OF SOIL FERTILITY IN CONSERVATION MANAGEMENT

Intrinsic limitations in the Soil Fertility characterization consist in the difference between what the soil indicators proposed to assess fertility in the *chemical-mineralist* conception demonstrate and what the plants perceive about the Soil Fertility condition (Nicolodi et al., 2014; Nicolodi and Gianello, 2017). *Intrinsic limitations* occur at all stages of the Fertilizer and Lime Recommendation Programs based on soil chemical analysis, even in areas under conventional tillage. In soil conservation management, especially under no-tillage systems (NTS), the increase in the occurrence and intensity of such *Intrinsic limitations* are related to the time of cultivation.

Intrinsic limitations in the sampling procedure refer to the representativeness of the area based on the collected soil sample. Although recommendations to collect 10 to 20 subsamples of the topsoil in areas under conventional tillage are generally used, it is not clear what error tolerance is allowed when determining the minimum number of subsamples that significantly represent an area for cultivation (Cline, 1944). In addition, the limits of statistical inference that provide accuracy and precision are not explicit, but they should not exceed the variations observed in the Quality Control Programs of Soil Analysis Laboratories (Wiethölter, 2001; Anghinoni, 2007). Such sampling procedures need to be even more careful in NTS, where the arable layer ceases to exist, giving way to another layer enriched with crop residues that forms a gradient of organic matter, acidity and nutrient availability from the surface downwards, which increase over time, changing the soil system dynamics and nutrient cycling (Sá, 1999).

The main causes of greater variability in Soil Fertility indexes under no-tillage systems are primarily due to the application of acidity correctives on the soil surface and fertilizers predominantly located in the seed row, where distance and depth vary from crop to crop. In this way, the non-tilling of the soil results in greater horizontal and vertical variability, which requires greater care in sampling. Sampling is also determined according to the type of collection equipment available (auger, probe and shovel) and the thickness of the layer to obtain representative samples within the parameters of statistical inference established by the Fertilization and Liming Recommendation Programs (Anghinoni, 2007).

The occurrence of *Intrinsic limitations* associated with the handling of the collected sample starts with drying, grinding and sieving the soil to 2.0 mm, which destroys the existing field structure. The availability of nutrients for plants in unstructured soil will be different from that in soil with preserved structure. This is because the porosity and aggregation properties directly affect the soil water retention capacity, which determines the diffusion process, especially of phosphorus and potassium, responsible for more than 90 % of the supply to the plant roots (Barber, 1995).

Furthermore, the mixture of soil collected in the traditional way from the 0.00 to 0.20 m layer could present a different result compared to the average of the 0.00 to 0.10 and 0.10 to 0.20 m layers, collected and analyzed separately. This is probably due to the gradient of acidity, organic matter and nutrients, especially available phosphorus, from the surface. In the case of phosphorus, high-energy adsorption reactions with the oxides in the clay fraction in weathered soils can result in different availability classes and, consequently, different fertilization recommendations (Anghinoni and Salet, 1998).

Another relevant aspect is to apply the precepts of conventional tillage in the characterization of the Soil Fertility status to soils under conservation management systems with a history of rotation and cover crops (Nicolodi et al., 2014) or under integrated crop-livestock systems (Anghinoni et al., 2018). The question is how to manage fertilization and liming, since a soil indicator with the same value, such as available phosphorus (Sousa et al., 1996; Schlindwein and Gianello, 2008) and potassium (Mielniczuk, 2005) and acidity (Martins et al., 2014) can be differently interpreted. Conservation management modifies the biological (microbial biomass and biochemical activity), physical (aggregation, aeration and water retention) and chemical (acidity and current and potential availability of nutrient supplying) properties. As a consequence, it is logical that there is a need to re-evaluate nutrient availability levels in relation to those for conventional tillage, such as critical nutrient levels, fertility ranges and classes, and recommendations for acidity correction and fertilization (Schlindwein and Gianello, 2008; Nicolodi et al., 2014; Fontoura et al., 2015), as the soil evolves in structure and functioning.

Attempts to reduce *Intrinsic limitations* in more complex production systems have been exhaustively presented and discussed by Nicolodi and Gianello (2015, 2016, 2017). According to these authors, these changes should be in the short term, of low cost and without substantially altering the procedures in use. This could be achieved by selecting more sensitive indicators to express the fertility perceived by plants, respective interpretation of the results, or even relating the normalized levels or values with crop productivity to identify groups of indicators that could characterize the different fertility levels. However, the results of these studies still expose a high magnitude of the *Intrinsic limitations* to the characterization of Soil Fertility and indicate that purely chemical evaluation is not sufficient to understand and express fertility, especially under conservation management, in which soil properties are built over time in a self-organizing process.

SOIL SYSTEM

To fully understand Soil Fertility, one must start from the premise that the soil is an open system and, therefore, ruled by the non-equilibrium thermodynamics laws (Prigogine, 1996). Its functioning stems from the magnitude and velocity of the continuous flow of energy and matter driven by organic compounds that permeate the soil system and place it in a condition far from the thermodynamic equilibrium (Vezzani and Mielniczuk, 2011).

The configuration of open systems is characteristic of the network pattern in which components are interconnected by non-linear relationships. Specifically, as Capra (1996) points out, the components of the system interact with each other, based on the internal relationships of each component, forming a network of relationships. In this network, the flow of energy and matter, which characterizes the exchanges between the soil and the environment through a network of non-linear relationships, generates energy dissipation and increases system activity and, in this situation, new organizational relationships between the components arise, outlining the process of self-organization within the soil system. Prigogine (2002) defines, as a dissipative structure, the system in which the dissipated energy promotes the emergence of another more probable organization that is characteristic of the configuration between the components and of the conjuncture of the magnitude and velocity of the flow. In this definition, probability and determinism are part of the self-organization process. In the soil, the flow of energy and matter with high magnitude and low velocity favors the emergence of more complex structures with the retention of energy and matter and, consequently, a high number of non-linear relationships (Vezzani and Mielniczuk, 2011). In each state of system organization, emergent properties resulting from non-linear relations are identified, which are in greater number and exert more functions the greater the number of components and, consequently, the connections between them. The self-organization process of the system is characterized by *evolutionary parameters* that, according to Vieira (2000), are in a gradual spectrum of increasing complexity: composition - connectivity - structure - flexibility - functionality - integrity. Here, we name the parameters with the terms that Vieira (2000) characterized to better associate them with the respective description. Thus, *composition* refers to the components that constitute the system; *connectivity*, the ability of components to form relationships with each other by mutually modifying; *structure*, to the number of relationships formed after a certain period of time; *flexibility*, the capacity of the structure to fragment into subsystems that remain connected to each other; *functionality*, to the functions resulting from the properties that emerge from the subsystems and from the subsystem sets; and *integrity*, to the more complex condition of functioning through numerous interdependent relationships that the system reaches after having evolved, going through all the previous phases (Mello, 2011; Vieira, 2000, 2013).

Associated with this continuum of self-organization and increasing complexity are the emergent properties of *synchrony*, when system components begin to function together; *synergy*, the components work better together; and *resilience*, the set of emergent properties generates the capacity of the system to maintain the level of functioning even with the occasional variations of the flow of energy and matter. Predicting the results of a system that organizes itself from the flow of energy and matter can only occur based on a sufficiently large amount of information (D'Agostini, 1999). The more complex the system - the greater the number of components and relationships - the more difficult it is to predict the effects of its functioning.

The restrictions imposed by the *Intrinsic limitations* allow us to infer that there are enough practical and theoretical elements to propose another concept of Soil Fertility, formulating a model that provides a better understanding of the systems that evolve and become more complex. In this sense, a systemic approach seems to be the best way forward. *Fertility must be understood as the ability to generate life and that it is not found in the soil, nor in plants, nor in animals, but in a dynamic set, integrated and harmonic, which is reflected in good soil properties, good plant production and good animal production* (Khatounian, 2001).

Thus, for soil analysis of an open system that self-organizes over time and reaches higher levels of complexity, when the necessary conditions are provided, the approach must be interpreted using a wider context than that currently used (D'Agostini, 1999). In this process, it becomes relevant to learn intellectually about the relationships that are formed and the properties that emerge as a result of this functioning: it requires the observer to use the capacity of comprehension, understanding and perception. It is more important to understand than to interpret (Mello, 2011). In this way, the observer also evolves when observing an evolving system.

SYSTEMIC SOIL FERTILITY CONCEPT

The concept of *Systemic Soil Fertility* here presented considers the understanding of the behavior of agricultural soils. The functioning of the soil can be oriented towards complexity as a result of changes in management practices adopted, ranging from the simplest in conventional tillage to multiple/complex in conservation management. The increase in the magnitude of flows of energy and matter and longer residence periods resulting from the non-linear relationships between mineral particles, organic compounds, plants and their roots, and organisms, promotes self-organization at levels of greater complexity, where new properties emerge, positively altering the functioning of the soil.

The initial condition for the evolution of Soil Fertility is inserted in the *chemical-mineralist* conception (Figure 1). It is representative of the vast majority of Brazilian soils with low fertility, either in their natural condition or because they have been subjected to long-term conventional tillage. The logic of Soil Fertility management under these conditions is to eliminate acidity and offer nutrients in sufficient and balanced amounts for plant development, which would respond with increased productivity. In the *chemical-mineralist* conception, the chemical analyses are the foundation of the evaluation of Soil Fertility.

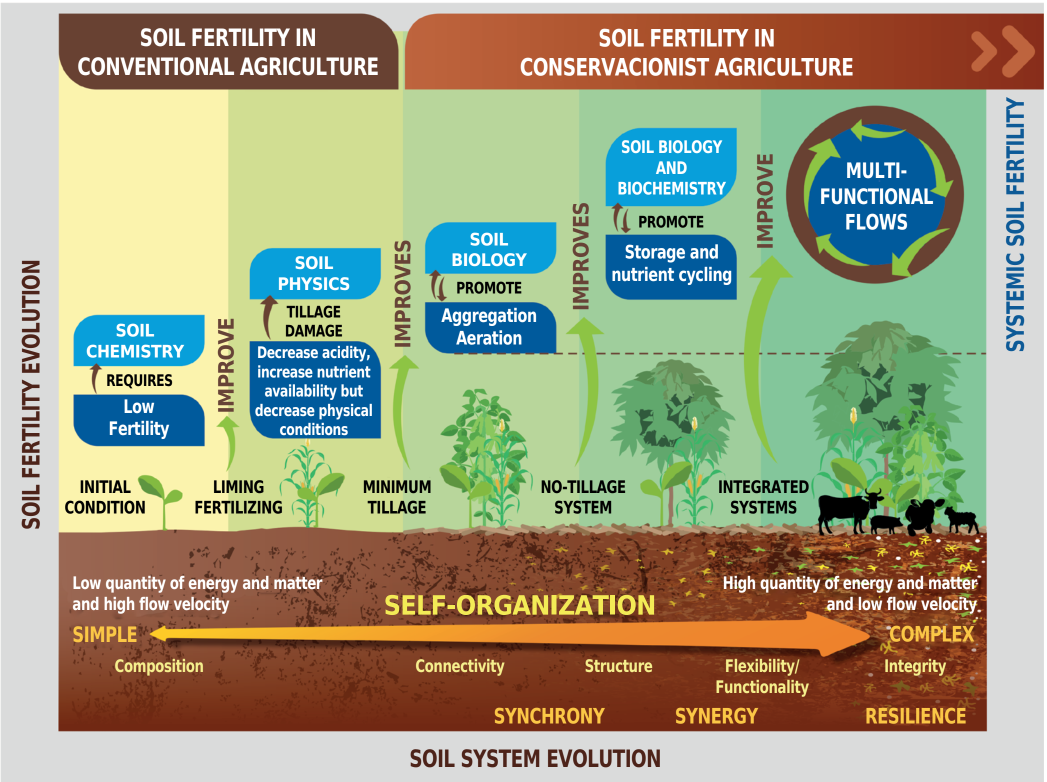

Figure 1. *Systemic Soil Fertility* as product of the self-organization of the system resulting from management. As management practices evolve towards increasing the magnitude and reducing the velocity of the flow of energy and matter, which results in longer residence time of organic compounds in the soil, the system changes from a simple structural condition to a complex one, in a self-organizing process. Along this path, soil properties (dark blue boxes) change in number and function, requiring that other Soil Science disciplines (light blue boxes) be considered to characterize Soil Fertility. The process of self-organization over time is identified by the evolutionary parameters of composition, connectivity, structure, flexibility-functionality, and integrity (Vieira, 2000) and the emergence of synchrony, synergy and resilience properties, showing the integration of components and their joint functioning until multifunctional flows are achieved, which provide both nutrient availability and stocks, fluxes of gases, water and solutes, and biological diversity and activity - which constitutes *Systemic Soil Fertility*.

The practice of liming and fertilization using this concept, in addition to not producing a substantial improvement in chemical properties, causes the loss of physical structure, compromises soil aggregation and aeration, due to its degradation that is a consequence of intensive soil mobilization (Figure 1) and also requires continuous addition of acidity correctives and fertilizers to maintain crop productivity.

Adoption of minimum tillage initiates the processes necessary for the recovery from physical degradation and the establishment of new relationships between the soil components, improving *connectivity* (Figure 1), an evolutionary parameter of the system (Vieira, 2000; Mello, 2011). In this condition, the components of the soil system self-organize into a new arrangement in order to promote greater fluidity of gases, water, and solutes and, thus, *synchrony* emerges, a new property, in which the system components begin to work together (Figure 1).

Reduction of tillage until there is no soil disturbance coupled with crop diversification are characteristics of no-tillage system (NTS), which increases new relationships between the components, providing better soil *structure* (Vieira, 2000; Mello, 2011). At this level of self-organization, the soil system has a greater capacity to retain energy and matter from the flows that pass through it. Thus, there is storage of nutrients and organic compounds, creating an environment more conducive to life in the soil that results in the emergence of *synergy*, demonstrated by biological and biochemical indicators (Figure 1).

At this stage, communities of soil organisms occupy different ecological niches and begin to perform ecosystem functions. Thus, the more complex the soil system, the greater the occurrence of soil niches that integrate and connect with each other, reaching a higher level of complexity with the emergence of new properties and functions (Figure 1). This level of self-organization is characterized by *flexibility and functionality* (Vieira, 2000; Mello, 2011).

Increase in the diversity of life forms and, consequently, the appearance of new properties, which were not present at lower levels of complexity, leads to the redesigning of production systems with the insertion of a greater number of productive factors in space and time. For example, crop diversification and integrated systems of agricultural production and successional agroforestry systems in conservation management. At this level of the evolutionary scale of management practices, the availability of nutrients from the cycling of crop residues and the labile fraction of organic matter occur simultaneously with crop demand, allowing the system to achieve a self-regulatory capacity (Figure 1).

With a greater number of components, the soil system self-organizes at a higher level of complexity, where relationships are abundant and lead to the plenitude of processes, generating multifunctional flows. This condition can be distinguished by biological and biochemical soil indicators and characterized by the evolutionary parameter *integrity*, the state of highest complexity and multifunctionality that a system can reach in terms of autonomy and permanence, ontologically defined in its organicity (Vieira, 2000; Mello, 2011) and the emergence of *resilience*.

Based on the presented framework, we are proposing the concept of *Systemic Soil Fertility* as a property that emerges from the synchrony, synergy and resilience of the soil system, resulting from a process of self-organization towards complexity, following an evolutionary order, which starts with *composition* and follows through *connectivity*, *structure, flexibility, functionality* and, finally, *integrity*. *Soil Systemic Fertility* concept results from the multiple relationships between the components of a complex system generated by the continuous flow of energy and matter, capable of providing the proper functioning of the soil, revealed in the availability and stock of nutrients, in the fluxes of gases, water and solutes and biological diversity and activity. This process of self-organization that occurs over time, promoted by the evolution of management, as shown in figure 1, starts from a soil with a simple structure that evolves into a complex structure, in which the components integrate and work together, constituting the foundation of *Systemic Soil Fertility*.

This concept results from a collective construction, where the contribution of each scientist group is identified along throughout this paper. The differential of our proposition is the theoretical basis and its *systemic approach*, in contrast to the *reductionist interpretation*. An attempt was then made to include the evolution in acquiring legitimate knowledge, with each piece of knowledge being integrated into our conception.

The *Systemic Soil Fertility* emphasizes the relevance of the relationships between the soil system components and this functioning that results from these relationships, which is the basis of non-equilibrium thermodynamics, the science that deals with the functioning of living (open) systems (Prigogine, 1996), such as the soil. This also is the scope of ecology, which studies the relationships between biotic and abiotic factors in the environment. Similar approaches are seen in studies on ecologically-based agriculture in which all system components – soil, plants and animals – are considered, as is the case of the Fertility of the System concept presented in Khatounian (2001). For this author, fertility belongs to the system, understood as the capacity to generate life, and its measurement is given by the capacity to produce biomass. We reinforce that our focus is on Soil Fertility. However, understanding the soil as an entity resulting from the relationships between its components, which are enriched and strengthened by the flow of energy and matter triggered by plants, and as the production system becomes more complex with respect to the number of cultivated species, the decrease in soil tillage and the inclusion of animals, the number of relationships and the resulting functions in the soil are intensified. A soil with abundant life, continuous porosity and available nutrients and water has, then, fertility.

IMPLICATIONS FOR SYSTEMIC SOIL FERTILITY MANAGEMENT

Based on the context and perception of Soil Fertility over time and ways of practicing agriculture in Brazil, the concept of *Systemic Soil Fertility* proposed here seeks to fill a gap in our understanding, arising from a reductionist approach to Soil Fertility. However, this proposal is not just a technical concept; it is necessary to use this understanding practically. Another category of knowledge of Soil Fertility is then proposed, which, in addition to agricultural experimentation, requires the acquisition of knowledge in the field of Soil Chemistry, Physics and Biology and Agronomy.

This proposal of the concept of *Systemic Soil Fertility* reduces the *Intrinsic limitations* of the *chemical-mineralist* concept of expressing Soil Fertility in long-term conservation systems, repeatedly pointed out by Nicolodi and Gianello (2016, 2017), and its understanding as a property generated by the functioning of the soil system. Regarding the intrinsic limitations in soil sampling, it is recommended to collect the true diagnostic soil layer, the number and distribution of points to satisfy the requirement of representativeness and statistical inference, considering soil management and time of cultivation. Such procedures are not clearly specified in the Fertilization and Liming Manuals currently in use in different Brazilian regions. However, in the case of consolidated conservation systems, especially the no-tillage system, it is recommended to sample the soil in the layers 0.00 to 0.10 and/or 0.00 to 0.20 m. In Rio Grande do Sul and Santa Catarina States, the recommendation is to collect the 0.00 to 0.10 m layer (CQFS-RS/SC, 2016) whereas in other states: São Paulo (van Raij, 1997), Minas Gerais (Ribeiro et al., 1999) and Paraná States (CFSNP PR, 2019) and in the Cerrado region (Sousa and Lobato, 2004), the sampling layer is from 0.00 to 0.20 m.

However, in management systems with diversified residue production (crop rotation, cover crops, pasture and successional agroforestry), with a resulting increase in organic matter, is necessary to evaluate the capacity for nutrient storage and cycling in addition to solely chemical analyses. To accomplish such requirements, the recommendation is to perform the soil analysis by layers: the assessment of chemical fertility is based on soil samples collected at the 0.00 to 0.20 m soil layer, and to evaluate the biological component (Soil Bioanalysis) on soil samples at 0.00 to 0.10 m layer (Mendes et al., 2019).

Under consolidated conservation systems, soils with corrected acidity, nutrients in the appropriate range (High and Very High classes), without physical restrictions and water availability, high residue production, high biological and biochemical activity, high nutrient cycling, and high structural and functional quality of the soil, fertilization becomes systemic (*fertilization of the system*) to meet the most demanding or most responsive crop in the production system (Anghinoni et al., 2013, 2019; Anghinoni, 2015; Fontoura et al., 2015). In this case, fertilization is annual, for replacement or maintenance (replacement + losses), preceding the most demanding crop or the one with the greatest response. In Central/South of Paraná state, fertilizer is applied to winter crops (wheat, barley, and white oats) in systems that include rotation with summer crops as soybean and corn and forage turnip as cover plant (Fontoura et al., 2015). In the case of integrated crop-livestock integration systems (ICLS), the fertilization occurs in the winter phase. In the highlands in Paraná (Assmann et al., 2018) and Rio Grande do Sul (Martins et al., 2015) states, fertilization is performed in ryegrass and/or oats succeeded by soybean and corn, and in the lowlands in Rio Grande do Sul State in the pasture phase succeeded by irrigated rice, soybean, and corn (Carmona et al., 2018).

CONCLUSIONS

The evidence that the current concept of Soil Fertility does not reflect the reality observed in agricultural production systems under conservational management was presented by the *Intrinsic limitations*, which means there are significant differences between the soil indicators proposed to assess fertility in the *chemical-mineralist concept* and what the plants actually perceive about the condition of Soil Fertility.

Intrinsic limitations are due to elevated productive agriculture under conservation management that results in high biomass addition, reflected in a continuous gain of energy and matter that permeates the soil system with an increase in soil organic matter over time and raises the agroecosystems to another functional level. The greater magnitude in the flow of energy and matter triggered by plants and the increased permanence of this energy and matter in the soil generates new configurations between the components in a self-organizing process leading to the emergence of more complex structures, identified by evolutionary parameters, with a higher number of relationships. In such a soil self-organization process, the *Intrinsic limitations* appear at the highest intensity level.

The understanding based on a systemic approach and soil perception as a living system has brought the multifunctional processes of the soil system to the forefront, requiring the disciplines of Soil Science knowledge to be considered holistically. Both the *Intrinsic limitations* and the soil system approach are the practical and theoretical bases sufficient to propose another concept of Soil Fertility.

Systemic Soil Fertility emphasizes the understanding the soil as an entity resulting from the relationships between its components, which are enriched and strengthened by the flow of energy and matter, triggered by plants, and as the system production system becomes more complex with respect to the number of cultivated species, and the decrease in soil tillage and the inclusion of animals, the number of relationships and the resulting functions in the soil are intensified. A soil with abundant life, continuous porosity, and available nutrients and water has, then, fertility.

Finally, the presentation of this concept of *Systemic Soil Fertility* aims to open a path for discussion in Brazilian Soil Science. Reflections and counterpoints will contribute to the advancement in the area of Soil Fertility and the understanding of the soil system as a whole.

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