International Union of Soil Sciences®

SUSTAINABLE SOIL MANAGEMENT AS A KEY TO PRESERVE SOIL BIODIVERSITY AND STOP ITS DEGRADATION

EDITORS:
Laura Berta Reyes-Sánchez
Rainer Horn
Edoardo A.C. Costantini

International
Decade of Soils
2015-2024

Sustainable soil management as a key to preserve soil biodiversity and stop its degradation

Editors:

Laura Bertha Reyes-Sánchez
Rainer Horn
Edoardo A.C. Costantini

International Union of Soil Sciences

2022

Eds: Laura Bertha Reyes-Sánchez, Rainer Horn, and Edoardo A.C. Costantini
Sustainable soil management as a key to preserving soil biodiversity and stopping its degradation

Please cite this publication as follows:

Reyes-Sánchez, L. B., Horn, R., Costantini, E. A.C. (eds.) 2022: **Sustainable soil management as a key to preserving soil biodiversity and stopping its degradation**. International Union of Soil Sciences (IUSS). Vienna, Austria.

Editor's address:
Laura Bertha Reyes-Sánchez *lbrs@unam.mx*
National and Autonomous University of Mexico. FES-Cuautitlán, Campo 4. Km. 2.5, Cuautitlán-Teoloyucan highway, San Sebastián Xhala, Cuautitlán Izcalli, Estado de México. C. P. 54714.

Rainer Horn *rhorn@soils.uni-kiel.de*
Institute for Plant Nutrition and Soil Sciences. CAU Kiel, Hermann Rodewaldstr, 2, 24118 Kiel, Germany.

Edoardo A.C. Costantini *eac.costantini@gmail.com*
CNR-IBE - Biology, Agriculture and Food Sciences Department, Sesto Fiorentino, 50019, Italy

Sponsor: International Union of Soil Sciences (IUSS)

ISBN: 979-8-9862451-0-2

Photo on book cover is pixabay.com
Photos, images, and drawings were provided by authors and are their responsibility

Foreword

Most organisms in terrestrial ecosystems develop at least a part of their life cycle in soil habitats or live in it, making the soil resource the most important reservoir of global biodiversity. Soil biodiversity plays a fundamental role in the proper functioning of all terrestrial ecosystems as well as economic, social, and human services that guarantee both human well-being and the existence of life on Earth.

Furthermore, soil healthy, nutritious food, climate change mitigation, as well as many other toral issues essential to our life, all depend on the knowledge of soil biodiversity.

Against this background intends the IUSS, as the leader in Soil Sciences at the worldwide level, to foreground the study of edaphic biodiversity from the broad interdisciplinary perspective, in order to promote the advancement of its area of knowledge.

In this regard, Soil Biodiversity was proposed as a current topic of great scientific, social, economic, and political importance for the present IUSS book as a document that had to be written from an interdisciplinary perspective and starting on the current state of the art in this area. A book written from the perspective of various points of view and interactions since the different areas of knowledge of soil sciences offered by the authors.

That is why the book contains both experimental data and conceptual information, didactic experiences, and reviews organized in four different sections showing points of view and interactions from the following knowledge areas of soil sciences:

* Soil Biodiversity perspectives from biological sciences point of view

* Interdisciplinary perspectives from agronomical point of view

* Interdisciplinary perspectives from soil physical point of view

* Interdisciplinary perspectives from soil chemistry and education point of view

Within the framework of the **"International Decade of Soils (IDS) 2015-2024"** and continuing with the objective of publishing and distributing material relevant to the interests of the IUSS and its members; an IUSS Open Access Book Series is launched under a Creative Commons license to download from the IUSS website in PDF format with free access for those who are members of the IUSS.

This book is the first of the Open Access Book Series of the IUSS.

Dr. Laura Bertha Reyes Sánchez
President of the International Union of Soil Sciences

UNAM, Mexico
May 19, 2022

Table of contents

Points of view and interactions from different knowledge areas of soil sciences

Soil biodiversity perspectives from biological sciences point of view

InterdiscipInary perspectives from agronomical point of view

Interdisciplinary perspectives from soil physical point of view

Interdisciplinary perspectives from soil chemistry and education point of view

Chapter 8

Conserving and enhancing above-and belowground biodiversities and their relationship with other properties in tropical soils: the success of Brazilian agriculture

Fatima Maria de Souza Moreira, Marcos Gervasio Pereira, and Eduardo Fávero Caires

Current scenario and prospects for Brazilian agriculture

The territorial extension of Brazil is approximately 845 million hectares (Mha), and about 7.6% of this area is used for crop production (*Figure 1*). This cropland area represents only 3.42% of the global cropland area – estimated at 1.873 billion hectares. In addition, about 180 Mha in Brazil is used as pasture (21% of the total geographic area). Areas dedicated to the protection, preservation, and conservation of native vegetation in Brazil total about 560 Mha (66%). In relative terms, the percentage of total geographic area devoted to cropland is lower in Brazil than in most countries.

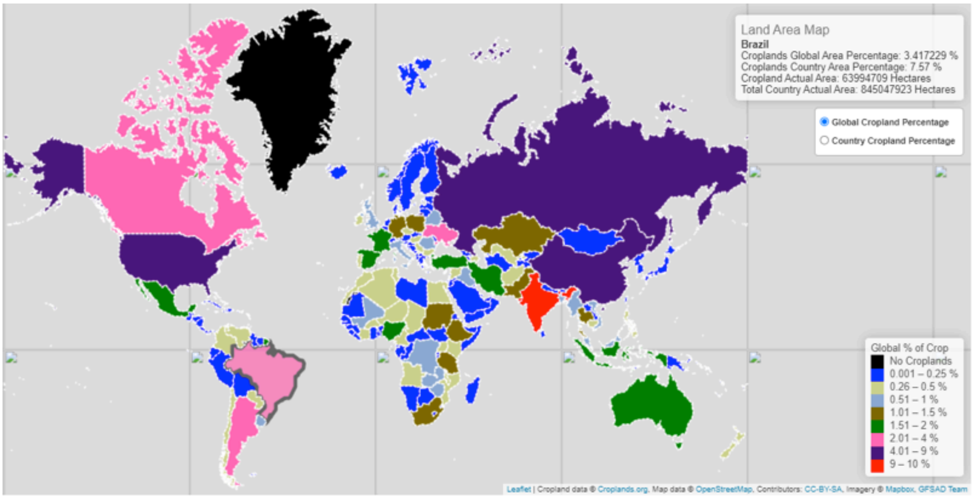


Figure 1. Image retrieved on 03 May 2021 from https://www.croplands.org/app/map/statsMap, maintained by the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC) at the USGS Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota, USA. 2018

The 7.6% occupation by cropland in Brazil contrasts with more than 80% in Moldova, San Marino, and Hungary; 70% to 80% in Denmark, Ukraine, Ireland, and Bangladesh; 60% to 70% of the Netherlands, the United Kingdom, Spain, Lithuania, Poland, the Gaza Strip, the Czech Republic, Italy, and India; and 18% of the United States of America (the USA) and

China. Globally, the largest net cropland areas are in India with 179.8 Mha (9.6% of global net cropland area), the USA with 167.8 Mha (8.9%), China with 165.2 Mha (8.8%), and Russia with 155.8 Mha (8.3%). Brazil ranks fifth, followed by Canada, Argentina, Indonesia, Australia, and Mexico. Brazil is recognized as an agricultural and environmental force since agricultural activities are conducted within an immense and diversified area of native vegetation.

The most prominent products of Brazilian agriculture are soybean (~136 million tons per year), maize (~109 million tons per year), sugarcane (~650 million tons per year), coffee (~2.8 million tons per year), orange (~17 million tons per year), cotton (~2.5 million tons per year), rice (~11 million tons per year), beans (~3,3 million tons per year), wheat (~6.5 million tons per year), cassava (~19 million tons per year), and cacao (0.25 million tons per year) (Conab, 2021). Grain production is gradually increasing in Brazil, along with the use of greater technology and modern cropping practices. Over the last 10 years (2010 to 2020), grain production in Brazil increased 70%, from 151 to 258 million tons (Figure 2). In this same period, cropland area increased only about 40%, from 47 to 66 Mha. The increase in grain production was mainly due to an increase in crop yields, showing the high sustainability of the growth of Brazilian agribusiness. Brazilian grain production is concentrated in the Midwest (46%) and South (32%) regions; the Southeast, Northeast, and North regions account for 10%, 8%, and 4% of grain production, respectively. Soybean and maize make up 85% of total grain production.

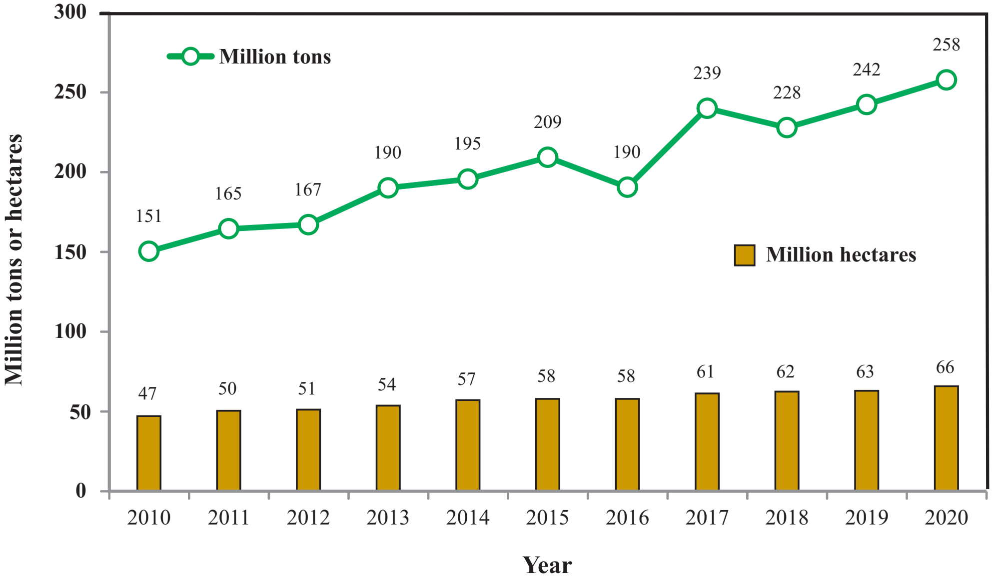


Figure 2. Expansion of grain production and cropland area in Brazil in the period from 2010 to 2020. Data obtained from Conab (2021).

Since Brazilian soils are highly weathered and have low nutrient reserves, increases in crop grain yield have been closely accompanied by increases in fertilizer consumption. Fertilizer deliveries to the agricultural market in Brazil increased from 24.5 million tons in 2010 to 35.5 million tons in 2018. Within this period, consumption of NPK fertilizers increased from 7.9 to 13 million tons (*Figure 3*). The average annual increase in the consumption of N, P, and K via fertilizers was 250, 100, and 285 thousand tons per year, respectively. Since soils in Brazil are naturally poor in P, they require relatively high P fertilization rates to ensure high grain yields. With soybean constituting about 45% of total grain production, slightly more K than N is used in fertilization. Soybean has both high efficiency in biological N_2 fixation and high K requirements, as large amounts of K are exported through harvests. Thus, N fertilization is often unnecessary in soybean, whereas the crop requires high input of K fertilizer.

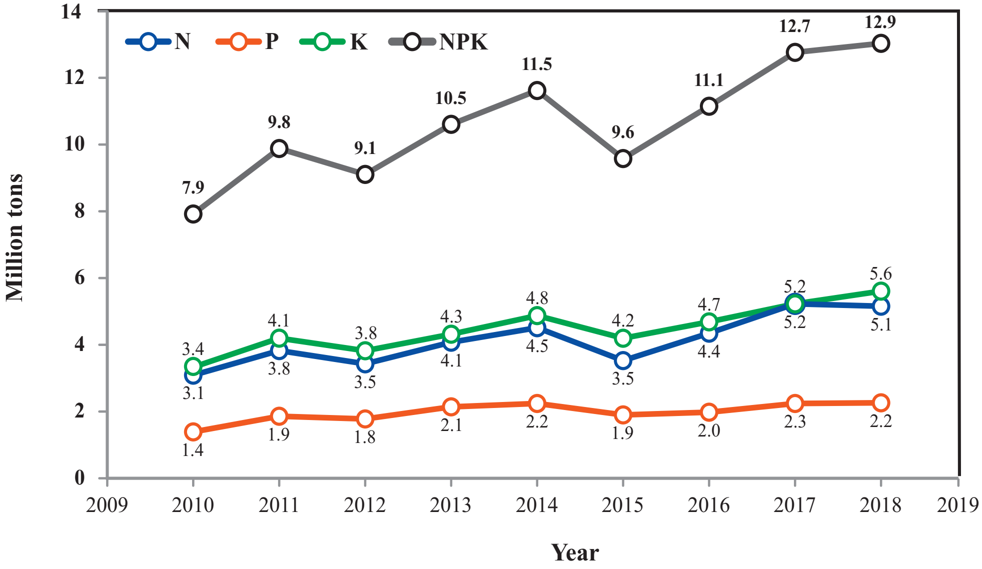


Figure 3. Evolution of NPK fertilizer consumption in Brazil in the period from 2010 to 2018. Data obtained from FAO (2021).

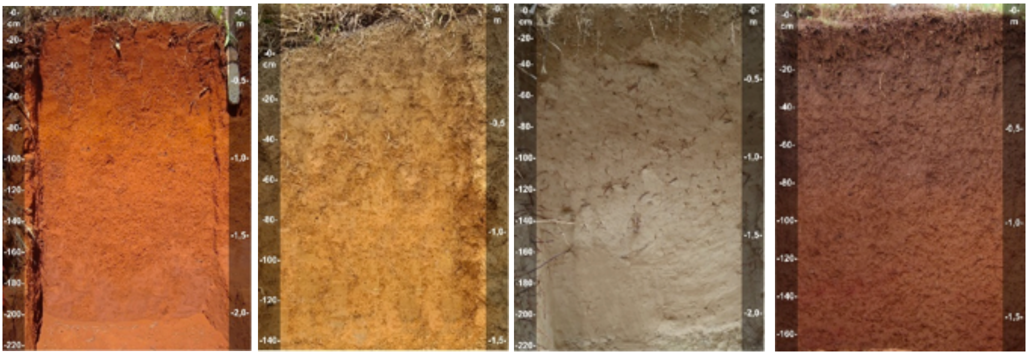
In this decade (2020 to 2030), Brazilian grain production is expected to increase to 318 million tons, while cropland area is expected to rise to 76 Mha. Internationally, expectations are that Brazil will have a nearly 52% share of world soybean exports and 23% share of maize and cotton exports. Such increases in grain production are expected to require even greater consumption of NPK fertilizers in Brazilian agriculture; therefore, fertilizer efficiency will be critical and fertilizer management practices should be improved.

A major challenge for expansion of Brazilian agriculture will be to achieve continual increases in crop yields with higher economic results while preserving soil natural resources and the environment. Greater investments are necessary in sustainable crop intensification processes and in recovery of degraded areas, with the aim of producing two or three crops per year in the same field through more complex cropping systems that have low greenhouse gas emissions and are adapted to climate change. Diversified production systems in no-till conservation agriculture and integrated crop-livestock and crop-livestock-forest systems, which are already in use in Brazil, should be improved and promoted. The use of cover crops and biofertilizers should be expanded, and other soil management practices related to improving the plant rooting profile should be adopted to conserve and enhance below- and aboveground biodiversity in such systems. These practices are expected to increase the carbon stock, nutrient cycling, water infiltration and storage, and soil productivity.

Properties of Brazilian soils

Brazil is a country of continental dimensions with great diversity of geological formations that function as parent materials, associated with wide climatic and topographic variability that contributes to generate soils with distinct morphological, physical, chemical, and mineralogical properties.

Latossolos (Ferralsols), *Argissolos* (Acrisols, Lixisols, and Alisols), and *Neossolos* (Fluvisols, Leptosols, Arenosols, and Regosols) constitute the main soil orders in Brazil (IUSS Working Group WRB, 2015). These three orders of soil together represent approximately 74% of the area in Brazil, and most of Brazilian cropland is composed of these soils. *Nitossolos* (Nitisols) are of limited occurrence compared to the previously mentioned soils, yet they have greater expression in the South region of Brazil, and due to their favorable chemical and/or physical characteristics, they are widely used for agricultural, silvicultural, and pasture activities (*Figure 4*).



(a) (b) (c) (d)

Figure 4. Main soil classes observed in the agricultural production areas of Brazil: (a) *Latossolo Vermelho* (Ferralsol); (b) *Argissolo Vermelho-Amarelo* (Acrisols, Lixisols, and Alisols); (c) *Neossolo Quartzarênico* (Arenosol); and (d) *Nitossolo Bruno* (Nitisol).

Each of these orders has specific characteristics that are the product of the action of pedogenetic processes, and due to these particular aspects, they display weaknesses and potentialities for agricultural use. The main characteristics and weaknesses of these orders are presented below.

Latossolos (Ferralsols) correspond to approximately 33% of Brazilian territory; they occur in all regions of Brazil, but have greater geographical expression in the North and Central-West regions. They are predominantly located in areas with flat to wavy topography and are deep and well-drained, which favors agricultural practices and minimizes erosion processes. Many *Latossolos* (Ferralsols) are acidic and have low nutrient reserves, which results in low natural fertility. Sometimes better natural fertility conditions are found when these soils are formed under drier climate conditions or produced from the weathering of basic rocks or sediments of a calcareous nature (Santos et al. 2018). They have kaolinitic and/or oxidic mineralogy with essentially variable or pH-dependent charges, which favors nutrient loss. Under higher acidity conditions, P fixation problems intensify. The reduced nutrient reserve of most *Latossolos* does not prevent them from being quite productive when well-managed, especially through use of techniques that maintain or increase the organic matter content, contributing to an increase in negative chargers in the soil.

Argissolos (Acrisols, Lixisols, and Alisols) are the order of second greatest occurrence in Brazil, corresponding to 28% of Brazilian territory, with greater expression in the North and Northeast regions. They have an accumulated clay horizon in the subsurface, which leads to slower flow of water inside the soil profile, favoring erosive processes, which can be intensified by the management practices used, the slope of the surface, and rainfall. *Argissolos* cover a huge range of soils, from those with high or low natural fertility to those with high saturation by aluminum. The cation exchange capacity of the clay fraction is variable, and soils with high and low activity clays can be observed. In addition, *Argissolos* are predominantly kaolinitic and have varying degrees of weathering. They have variable depth and can be seen in areas of topography ranging from flat to strongly wavy; their drainage can be good to imperfect.

Neossolos (Fluvisols, Leptosols, Arenosols, and Regosols) are mineral soils that have a lower degree of pedogenetic development, which may be due to topographic conditions that favor greater intensity of erosion processes, promoting constant rejuvenation of the soils; climatic conditions that disadvantage the weathering processes; the short time of formation of the soil; or the resistance of the parent material. These factors limit soil evolution. This order includes the following suborders: *Neossolos Litólicos* (Leptosols), *Neossolos Regolíticos* (Regosols), *Neossolos Quartzarênicos* (Arenosols), and *Neossolos Flúvicos* (Fluvisols).

Neossolos Litólicos (Leptosols) have varied natural fertility dependent on the nature of the parent material. The main limitation is the shallowness of the soil, which restricts root system development, water storage, and management practices. The location of these soils in the sloping reliefs also allows erosion processes to occur at greater intensity. *Neossolos Regolíticos* (Regosols), located in sloped areas, are deeper than *Neossolos Litólicos*, and generally have limitations similar to those observed for *Neossolos Litólicos* (Leptosols).

Neossolos Flúvicos (Fluvisols) are formed predominantly by fluvial sediments, with variable fertility and activity of the clay fraction. They have potential for agricultural use, but when located close to river areas, they may be subject to waterlogging in periods of greater rainfall, limiting agricultural mechanization and causing oxygen deficiency. They can also be used for environmental preservation when located in riparian forest areas.

Neossolos Quartzarênicos (Arenosols) are soils that have a sandy texture, with predominance of quartz. They are environmentally fragile because they have high susceptibility to erosion, low water storage capacity, and high losses by leaching, which can lead to aquifer contamination. In addition, the sandy texture favors rapid decomposition of organic matter. These soils have considerable geographical expression in the region called MATOPIBA, which encompasses part of the states of Maranhão, Tocantins, Piauí, and Bahia, a region that in recent years has witnessed great expansion of the agricultural sector (Donagemma et al. 2016).

Despite their limited extension compared to other soils (1.3%), *Nitossolos* (Nitisols) have wide agricultural use in the South region of Brazil, especially for grain cultivation. They are deep soils, with a clayey or very clayey texture and an accumulated clay horizon. Differentiation between their horizons is less pronounced compared to *Argissolos*, which helps impede erosion processes of great intensity. They may have good natural fertility, but are moderately acidic to acidic, with predominance of low or high activity clays of kaolinitic-oxidic composition.

Due to the intense weathering conditions to which most Brazilian soils were subjected in their formation, iron and aluminum oxides and kaolinite are the main constituents of the clay fraction (Kämpf et al. 2016). These minerals have low cation exchange capacity and can sometimes exhibit anion exchange capacity, a phenomenon that can be observed in iron oxides. Due to these characteristics, management systems that contribute to an increase in the organic matter content in soils are of fundamental importance.

Crop production systems

Before and after no-till conservation agriculture

In Brazil, conventional agriculture with intensive tillage through plowing and harrowing has led to large losses of soil by erosion, causing severe environmental degradation and loss of soil productive capacity. In the South of Brazil, with more slopy areas and higher rainfall intensity, intensive tillage led to an unsustainable condition of extensive soil erosion, and agriculture was at risk (*Figure 5*). This situation of widespread soil degradation persisted through the 1960s. Even though building terraces and contours helped check runoff and surface layer losses, it rarely curtailed erosion sufficiently to make this production system viable. In response, concerned farmers and researchers gradually began to look for other more sustainable production technologies.

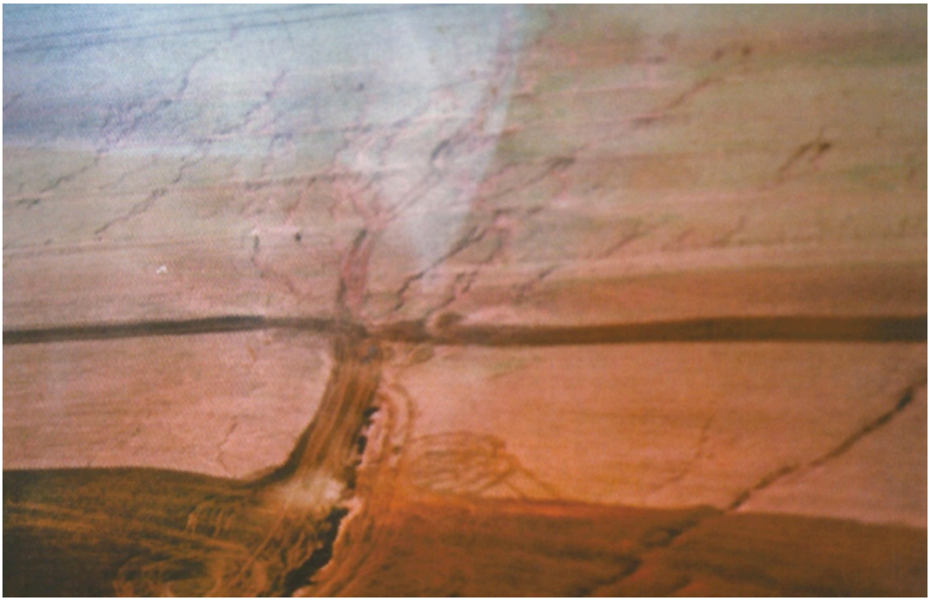


Figure 5. Water erosion processes resulting from intensive tillage in the Campos Gerais do Paraná, PR, region, southern Brazil (1970). Image obtained from Dijkstra (2020).

Conservation agriculture based on no-tillage systems (no-till) began to be practiced in southern Brazil in the early 1970s. No-till farming had three basic principles: (i) no soil disturbance, (ii) permanent soil cover by crop residues or cover crops, and (iii) crop rotation. In this cropping system, crops are seeded into untilled soil by opening only a narrow slot, trench, or band of sufficient width and depth to obtain proper seed coverage; no other soil tillage is done.

Residues from previous cash crops or green manure cover crops are to remain undisturbed on the soil surface after sowing. Crop rotation and growing cover crops are essential practices in this system.

The evolution of no-till farming in Brazil has been well documented (Bolliger et al. 2006, Calegari et al. 2020). No-till farming had limited expansion throughout the 1970s mainly due to the lack of suitable techniques to effectively control weeds, as well as the lack of planters able to work with large amounts of residues. During this period, planters had to be adapted and only 2,4-D and paraquat herbicides were available for weed management. The release of glyphosate in Brazil in the mid-1970s and the improvement of agricultural machinery boosted no-till farming in the 1980s. In addition, in the 1980s, no-till farming began to be used in the tropical, wet-dry savannah region (*Cerrado*) of central Brazil. Even so, the expansion of cropped area under no-till in Brazil was still slow until the early 1990s, when no-till farming reached about 1 million ha. It was from the 1990s on that cropped area under no-till greatly expanded, both in southern and central Brazil. The genetically modified (GM) crop technologies introduced in the 2000s further facilitated weed control using glyphosate. Currently, Brazil is one of the leading countries in the world in adoption of conservation agriculture based on no-till. The latest official information from the Brazilian agricultural census (IBGE, 2019) indicated that no-till farming is used on 33 Mha. Based on the rate of increase in cropped area under no-till in the last 10 years in Brazil, the cropland area under no-till farming is expected to expand to 40 Mha by 2030.

After the “Green Revolution” that brought a series of benefits to Brazilian agriculture, the change in cropping systems to conservation agriculture based on no-till was the biggest agricultural revolution in Brazil. No-till systems with rotation of diverse crops minimize soil and nutrient losses from erosion and increase organic carbon and nitrogen content through increased deposition of plant residues and decreased soil disturbance (*Figure 6*). The increase in soil organic matter increases cation exchange capacity (CEC), biological activity, and biodiversity.

Figure 6. Maize sowing and soybean emergence in no-till systems in the Campos Gerais do Paraná, PR, region. Images obtained from Dijkstra (2020).

One of the biggest challenges in no-till farming is to produce straw/plant residue in sufficient quantity and quality that remains on the soil surface to increase biodiversity and provide sustainability to this cropping system. Proper management of no-till requires the addition of at least 10 Mg ha^{-1} year^{-1} of dry phytomass, including legumes in crop rotation, which promote nitrogen input and organic matter accumulation (Bayer and Dieckow, 2020). High straw production is also important for more efficient weed control. This is a highly relevant aspect because there is currently considerable concern over increased use of glyphosate in GM glyphosate-resistant crops. Intensive glyphosate use has led to the selection of glyphosate-resistant weeds and microorganisms, changing microbiomes (van Bruggen et al. 2018). Increasing the production of straw that remains on the soil surface under no-till decreases weed infestation and helps reduce the use of herbicides, including glyphosate. A problem occurs in areas with low soil cover production, where farmers have increased the dosage and frequency of glyphosate for greater weed control. Improvements in this area and more research are necessary to allow farmers to verify that greater and more diversified production of cover crops not only decreases the use of herbicides and improves the ecosystem, but also results in greater economic return. No-till cropping systems require adequate strategies for supplying straw by integrating fast-growing cover crops and cash crops into the rotations.

In Brazil, several cover crop species have been used in no-till conservation agriculture. In subtropical southern Brazil, the most used cover crop species are black oat (*Avena strigosa* Shreb), radish (*Raphanus sativus*), hairy vetch (*Vicia villosa*), common vetch (*Vicia sativa*), field pea (*Pisum sativum subsp*. arvense), lupin (*Lupinus albus*), rye (*Secale cereale*), and rye grass (*Lollium multiflorum*). In the tropical Brazilian Cerrado region, the preferred cover crop species are millet (*Pennisetum americanum*), Crotalaria (*C. spectabilis, C. ochroleuca, C. juncea, C. breviflora*), buckwheat (*Fagopirum esculentum*), cowpea (*Vigna unguiculata*), pigeon pea (*Cajanus cajan*, normal, dwarf), *Mucuna aterrima* (grey, black, dwarf), lablab (*Dolichos lablab*), *Clitoria ternatea,* Sudan grass (*Sorghum* × *drummondii*), *Stylosanthes* sp., pinto peanut (*Arachis pintoi*), sunflower (*Helianthus annuus*), *Urochloa spp*. (syn. *Brachiaria*), *Paspalum* sp., and Guinea grass (*Panicum maximum*) (Calegari et al. 2020). Mixing cover crops has also been encouraged to increase the biodiversity of production systems. Mixed cover crops include two, three, four, or more species; for example, black oat + vetch, radish + black oat + vetch, buckwheat + radish + pearl millet, *Crotalaria* sp. + pearl millet or *Cajanus cajan* + pearl millet + *Crotalaria* sp., or pearl millet + *Crotalaria* sp. + buckwheat. As soil and climate conditions vary, each cropping system should have a mixture of cover crop species that are more suitable for fulfilling multiple functions in the soil. This is an important subject and of great interest in interdisciplinary research.

After about 50 years of no-till in Brazil, this cultivation system appears to have changed the original concept of agriculture entirely, bringing a great deal of learning and countless benefits. The success of no-till is based on accumulation of organic matter and an increase in below- and aboveground biodiversity. This requires diversification of cropping systems, high input of crop residues, and no impediments to plant root growth along the soil profile. These are aspects of concern in current no-till conservation agriculture in Brazil. Because of the usual surface applications of lime and fertilizers in no-till, the improvement in soil fertility in this cropping system has been largely restricted to the topsoil. For that reason, research on soil management practices that may favor the growth and deeper penetration of root systems in the soil profile (such as the use of lime, gypsum, polyhalite, cover crops, animal waste, and biofertilizers capable of promoting plant growth through hormone synthesis) should be encouraged. Some crops with specific deep rooting characteristics can improve subsoil structure. Taproot systems such as alfalfa (*Medicago sativa*) have specific pore geometries associated with structure related air-filled porosity and biopore formation. Uteau et al. (2013) found that alfalfa generated a greater connected air-filled porosity due to more intense shrinking/swelling processes. Although Brazil produces only 40 thousand hectares of alfalfa, mainly in the southern region, there is great potential for the expansion of its cultivation in Brazil. The expansion of the area cultivated with alfalfa could help in the recovery of the soil structure following intensive crop production. Increasing root growth in the soil profile increases the carbon stock in deeper layers and helps curb greenhouse gas emissions. Cooper et al. (2021) observed that the larger carbon content within no-tilled aggregates translated into a greater total carbon content throughout the soil profile (0–50 cm). Differences in carbon stocks at greater depths have been explained by better root growth conditions under no-till (Galdos et al. 2019). Sisti et al. (2004) showed that increased carbon accumulation in no-till soil below 30 cm depth could be explained by greater root density when compared with conventional tillage. In addition, world commodity markets have caused an overemphasis on soybean growing in Brazil, putting crop diversification at a certain risk. Since this reality will likely not change, at least in the short-term, greater efforts are necessary to increase diversification and the input of cover crops right after soybean harvest. This is a greater concern in the tropical Cerrado region, where sufficient moisture is usually available only in the spring-summer season, from October to March (*Figure 7*). Some techniques of overseeding forage species, such as *Urochloa* (syn. *Brachiaria*) *ruziziensis*, U. *brizantha*, and *Panicum maximum* cv. Mombaça through broadcasting by airplane at the end of the soybean crop cycle (development stage R5.5), have shown excellent results in integrated crop-livestock production systems. In addition, a second crop of maize intercropped with these forage species following soybean has provided several benefits and should be encouraged. The main objective is to keep the system biologically active by constantly adding organic residues and increasing biodiversity.

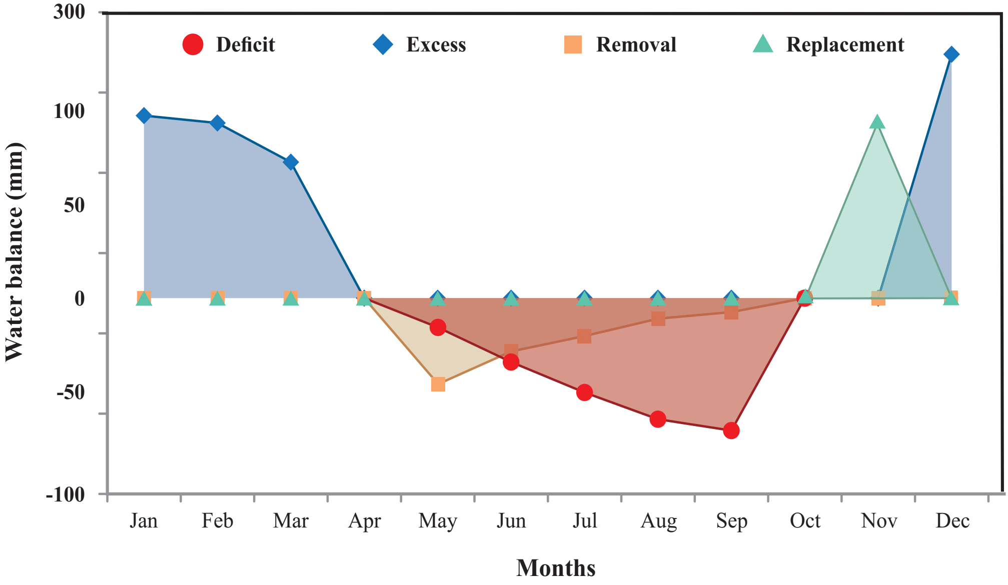


Figure 7. Extract of the normal climatological water balance for the period between 2004 and 2013, considering the soil water storage capacity of 100 mm at the Main Station of Embrapa Cerrados, Planaltina, DF, Brazil. Source: Silva et al. (2017).

Establishing integrated crop, pasture, forest, and livestock systems

Soils Brazilian institutions linked to the National Agricultural Research System (Embrapa) have long recommended systems based on no-till farming that integrate agriculture and livestock (Balbino et al. 2011). One of these systems is crop-livestock integration (CLI) and, more recently, the forest component was incorporated, creating the crop-livestock-forest integration system (CLFI).

Integrated agricultural production systems are sustainable strategies, designed to exploit synergies and intensify land productivity, combining annual agricultural, livestock, and/or forestry activities in different spatiotemporal arrangements. These systems contribute to changes in the physical, chemical, and biological properties of the soil (Vinhal-Freitas et al. 2010), promoting improvements in land quality (Lemaire et al. 2014). Therefore, they can help combat global food and energy insecurity and climate change in the coming decades (Moraes et al. 2014, Bieluczyk et al. 2020).

These systems began to be more widely used in the 1990s, and long-term experiments were developed with grain crops in association with pastures, especially in the South region of Brazil (Balbino et al. 2011) and then reproduced in other regions, with adaptation to environmental and cultural realities.

According to the FAO (2010), integrated production systems have the following benefits: i) improvement of production processes in the workforce, stability of economic factors, and risk reduction; ii) greater chances for producers to achieve their socio-cultural aspirations in an equitable way; and iii) greater food security to meet the needs of consumers regarding the quality of products and production processes.

According to Balbino et al. (2011), integrated production systems can be classified into four distinct modalities: (i) CLI or agropastoral, a production system that integrates agricultural and livestock components in rotation, consortium, or succession in the same area and in the same agricultural year or for multiple years; (ii) LFI or silvopastoral, a production system that integrates livestock (pasture and animal) and forestry components in consortium; (iii) CFI or silvoagricultural, a production system that integrates the agricultural and forestry components through the intercropping of tree species with agricultural crops (annual or perennial); and (iv) CLFI or agrosilvopastoral, a production system that integrates agricultural, livestock, and forestry components in rotation, consortium, or succession in the same area. The crop component can be restricted to the initial phase of implantation of the forest component or be part of the system for several years. Among these modalities, the one that has been most prominent in Brazil is the CLFI (Kichel et al. 2014). Some examples of integrated production systems are shown in *Figure 8*.

Figure 8. Silvopastoral integration production system (a) and agrisilvicultural integration production system (b), Embrapa Pecuária Sudeste. Source: Wanderlei Bieluczyk.

Assessing the effect of the CLFI system in Cerrado areas, Zago et al. (2019) found that the system had a positive effect on microbial biomass and soil enzymes compared to pasture, reinforcing the importance of adopting more sustainable practices for soil health. In another study assessing the impacts of CLFI on soil microbiological indicators, Stieven et al. (2014) observed that, in general, the CLFI systems had positive impacts on soil microbiota.

Other authors, such as Assis et al. (2015), studied changes in the physical properties of the soil due to implementation of CLFI systems and found that such systems led to improvement in soil physical quality, identified by the improvement of the following attributes: hydraulic conductivity, microporosity, total porosity and bulk density, in relation to degraded pasture.

Studying the effect of nominal extensive grazing to CLI, and CLI to CLFI, system conversion on the quantity, quality, and origin of soil organic matter in southeastern Brazil in a six-year experiment, Bieluczyk et al. (2020) found that all the systems increased soil carbon and nitrogen stocks throughout time. In this study, CLI and CLFI systems enhanced 21% and 17% of soil carbon from 2010 to 2016. However, when comparing soil C accumulation tendencies in time (estimated by four points linear regression), converting extensive low-grazing intensity pasture to ICL was the most promising strategy, increasing soil C stocks at the rate of 0.28 Mg C ha^{-1} yr^{-1}. Further intensification, from CLI to CLFI reduced -0.22 Mg C ha^{-1} yr^{-1}, bringing no further benefits on soil organic matter accrual.

Agroforestry systems

Agroforestry systems (AFSs) are based on ecological succession and are analogous to natural ecosystems. Exotic or native trees are intercropped with agricultural crops, vines, forages, shrubs, etc. according to a pre-established spatial and temporal arrangement, with a high diversity of species and interactions among them. These systems are based on ecological, economic, and social interactions that exist in a production system, playing multiple roles such as promoting the recovery of degraded areas, ecosystem services and increased biodiversity, among others. In the Amazon, AFSs, called "terreiros", with a great diversity of native fruit and medicinal species and multiple uses, are commonly found close to rural indigenous communities, conserving biodiversity, including non-conventional plant species and increased soil organic matter (Noda et al. 2008).

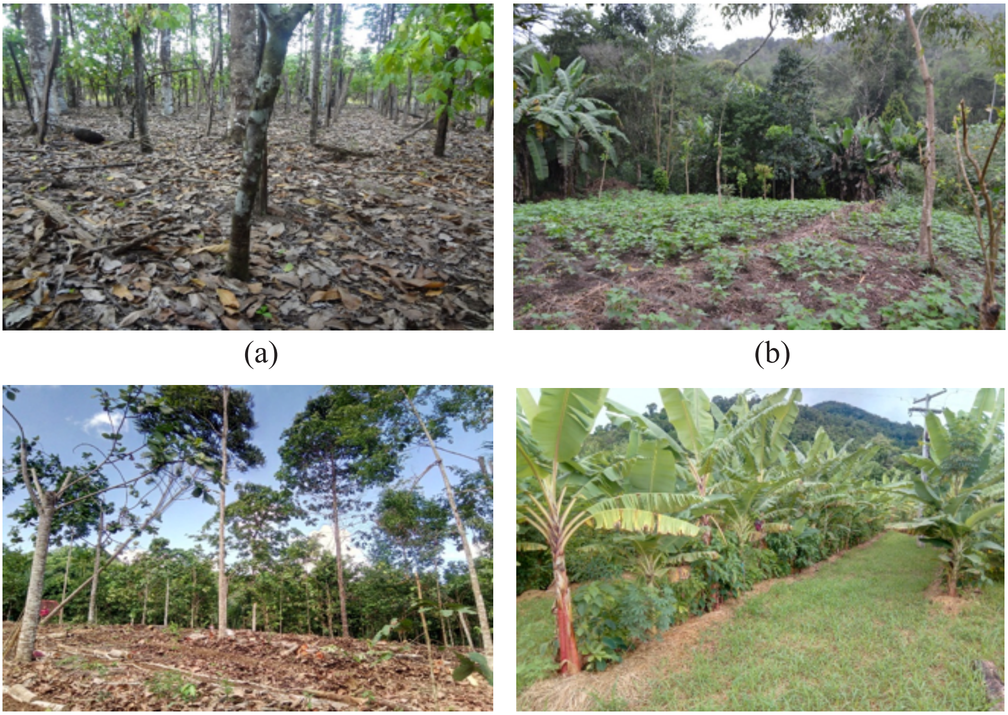
AFSs have been considered more sustainable agricultural systems than traditional forms of agriculture and forestry. They can function as a viable option for the recovery of degraded areas, management of forest fragments, forest restoration in areas of permanent preservation and legal reserves and in the establishment of small plots with tree species for the purpose of producing wood for the producer's own consumption or as a source of food items. They provide various ecosystem services, such as carbon sequestration, biodiversity conservation, maintenance and/or improvement of soil fertility, prevention and reduction of erosion processes, improvement of water infiltration, wind break protection, pest control, and pollination enhancement. The great diversity of plant species creates favorable conditions for establishing ecological and environmental functions on the property, allowing for better stability of laborers in the field and greater income security for the producer, due to product diversification (Chang and Cheng, 2020). These systems have been identified as an alternative for more sustainable development of agriculture, especially for developing countries (Matthews et al. 2014, Nair et al. 2010).

In Brazil, regional diagnostics and research results have shown that AFSs are highly applicable in areas with agricultural and livestock activities. The main projects have been associated with cacao (*Theobroma cacao*), rubber (*Hevea brasiliensis*), oil palm (*Elaeis guineenses*), and coffee (*Coffea canephora* and *Coffea arabica*) crops (Alvim and Nair, 1986; Brienza Junior and GazelYared, 1991; (Souza et al. 2012, Gama-Rodrigues et al. 2010, Jagoret et al. 2014, Monroe et al. 2016, Ramos et al. 2018). In addition, other studies have shown that AFSs have good responses when used in areas where there are problems in different ecosystems resulting from deforestation and degradation.

This pattern was observed by Fávero et al. (2008), evaluating the recovery of degraded areas through an agroforestry system in the Vale do Rio Doce, Minas Gerais.

In general, AFSs can be classified into (i) agrisilvicultural systems that involve agricultural crops and trees, including shrubs and/or vines; (ii) silvopastoral systems that refer to the association of pastures and/or animals and trees; and (iii) agrosilvopastoral systems that combine agricultural crops, pastures and/or animals, and trees. In any of these systems, integration of the components can take place simultaneously or sequentially and in an infinity of possible combinations (https://www.embrapa.br/en/codigo-florestal/sistemas-agroflorestais-safs).

Through integration of trees in agricultural systems, production is diversified and sustained, promoting an increase in social, economic, and environmental benefits for land users at all levels. In particular, agroforestry systems are crucial for small farmers and other rural populations as they can promote an increase in the food supply, income, and health (http://www.fao.org/forestry/agroforestry/80338/en/). Some examples of AFSs in different regions of Brazil are shown in *Figure 9*.



(a) (b)

(c) (d)

Figure 9. Agroforestry Systems composted of African mahogany and cacao, Tomé-Açu, PA, Brazil (a), source: Prof. Alberto Bentes Brasil Neto; AFS at the Universidade Federal de Santa Maria, Santa Maria, RS, Brazil (b), source: Prof. Ricardo Bergamo Schenato; Renovation of AFSs Jaguaquara, BA, Brazil (c), source: Prof. André Mundstock Xavier de Carvalho; and AFS including banana and cassava, Jaguaquara, BA, Brazil (d), photo: Prof. André Mundstock Xavier de Carvalho.

Assessing soil organic carbon storage in cacao (*Theobroma cacao* L.) AFSs in Bahia, Brazil, Gama-Rodrigues et al. (2010) highlighted the role of this system in mitigating the emission of greenhouse gases (GHG) through the accumulation and retention of large amounts of organic carbon in soils, demonstrating the benefit of the environmental services promoted by this system.

Monroe et al. (2016) quantified soil organic carbon storage and assessed its origin as an indicator of the relative contribution of trees (C3 plants) and grasses (C4 plants) four years after converting pasture to AFSs in southern Bahia. They observed that AFSs using cocoa and rubber were the most efficient systems in accumulating carbon in the first 20 cm of soil, and that AFS with cocoa was more efficient than with rubber in accumulating carbon derived from C3 plants. The C3-origin SOC decreased according to the following sequence: cacao row > natural forest > rubber row > pasture. In addition, the C4-origin SOC decreased according to the following sequence: pasture > rubber row > cacao row. The C3-origin C in the rubber row increased by 59.9 Mg ha^{-1}, and the C3-origin C in the cacao row increased by 81.7 Mg ha^{-1}at a depth of 0–20 cm after 4 years of establishment. The C4–C3 replacement rate in the rubber and cacao rows were 5.25 Mg ha^{-1}year^{-1} and 8.60 Mg ha^{-1}year^{-1}, respectively.

In eastern Amazonia Ramos et al. (2018), quantified C stocks in a palm oil (*Elaeis guianensis* Jacq.) AFS and a palm oil AFSs associated with cacao (*Theobroma cacao* L) in four distinct compartments: aboveground live biomass, plant litter, roots, and soil. The carbon stock until 30 cm depth was higher in the palm oil AFS with cacao (116.7 ± 1.5 Mg C ha^{-1}) compared to the AFS with palm oil only (99.1 ± 3.1 Mg C ha^{-1}). The same pattern was observed for the total plant litter stock, which was higher in the palm oil AFS with cocoa (3.27 ± 0.01 Mg C ha^{-1}) than in the palm oil AFS (2.26 ± 0.06 Mg C ha^{-1}). For the total stocks of root and soil carbon (0-30 cm), there were no significant differences between the AFSs. Carbon stocks varied between AFSs due to differences in above- and belowground stocks. In general, C stocks below ground varied spatially in response to management in the oil palm and non-palm areas. The results obtained have important implications for monitoring carbon dynamics at the ecosystem level and the refinement of soil management

Martinelli et al. (2019) studied aspects related to the mitigation of global warming and the provision of ecosystem services for small farmers in the Cerrado biome and found that AFSs have significant carbon sequestering capacity, represented by the negative values of global warming potential, ranging from (−263) to (−496) t CO_2 equivalent per hectare. In addition, it was noted that a large number of fruit trees allowed farmers to consume and sell a wide variety of products. Through adoption of the system, families also benefited from improvement of microclimate conditions and the aesthetic effects provided by the AFSs.

Plant biodiversity and its implications for soil quality

Brazil is well known for the megadiversity of its six biomes, consisting of vegetation with very heterogeneous characteristics (IBGE, 2019). This megadiversity is a consequence of the vast area of Brazil of mainly tropical climate, but also includes subtropical and temperate climates and a wide diversity of soils. For instance, at least 2.000 native Leguminosae species is estimated to occur in Brazil (Moreira, 2006). This figure represents 10% of all Leguminosae species throughout the world. Plant diversity also extends to edible plants, with some species typical of the cuisines practiced in each region of the country and generally grown by small farmers who maintain the diversity (many varieties) of this priceless germplasm. Some examples are *Euterpe* spp. (açaí), *Theobroma grandiflorum* (cupuaçu), and *Solanum sessiliflorum* (cubiu) in Northern Brazil; *Caryocar brasiliense* (pequi) in the Central-West; *Araucaria angustifolia* (araucaria) in southern Brazil; and even unconventional plants such as *Pereskia aculeata* (ora-pro-nobis), very popular in Minas Gerais in the Southeast of Brazil. *Vigna unguiculata* (cowpea) and *Phaseolus lunatus* (lima bean) are typically cultivated by small farmers, who preserve many subspecies and varieties in the North and Northeast of Brazil, where they are predominantly grown.

Considering epigeic and anecic organisms, such as some earthworm species, are known as components of soil biodiversity, it is logical to also consider plants as soil organisms, even more so because the root system of many species is much larger in volume and biomass than their shoots. Diversity in plant species that inhabit the soil provides for diversity of carbon substrates, due both to decomposition of deposited organic matter (plant residues) and the effect of plant roots (rhizosphere effect), which exude a great diversity and quantity of organic compounds that nourish soil organisms at different levels of the food chain under different vegetation covers (Berendsen et al. 2012, Kou et al. 2018). Thus, these carbon substrates allow the activity of all soil organisms to act as a driving force for biophysical (e.g. improvement of aggregation of soil particles by exopolysaccharides produced by fungi and bacteria as well as by fungal hyphae, improvement of water and air movements in tunnels, galleries and other structures made by soil fauna) and biochemical processes (e.g. nitrogen fixation, inorganic phosphate solubilization, organic matter decomposition and mineralization) that ensure the sustainability of ecosystems. As the main primary producers, plant species are the basis of food web and allow other groups of organisms (decomposers, litter and soil organic matter feeders, mutualists, pathogens and parasites, shredders, grazers and predators) to survive and provide ecosystems services. For instance, Braga et al. (2012) showed that land-use intensification (forest to pastures) in western Amazonia results in a reduction of the richness, abundance and biomass of dung beetles, and this in turn results in lower rates of dung removal as well as higher number of flies in the most simplified systems (pastures). Moreover, maintaining and enhancing biodiversity is of utmost importance to provide genetic resources for a great diversity of purposes, including agricultural management. Therefore, plant diversity is fundamental for soil quality.

The various production systems in constant expansion in Brazilian agriculture, such as no-till planting, crop-livestock integration, crop-livestock-forest integration, and agroforestry, consider the diversity of plant species and the conservation of plant residues on the ground (see 3.2 and 3.3). The use of trees in pasture also provides for animal welfare. The expansion of these types of management will certainly require species that contribute to food security, and their growth will be stimulated by biological processes.

Contribution of soil biodiversity to the sustainability of cropping systems in Brazilian soils and challenges in increasing utilization

Awareness of the importance of soils and their biodiversities have increased exponentially in recent years (FAO et al. 2020, Orgiazzi et al. 2016). Likewise, the development of reliable and accurate techniques for assessing and understanding biodiversity, especially microbial diversity, has increased exponentially. However, management of this biodiversity for sustainable agriculture and food security has not been developed in the same way. Development of molecular techniques has allowed evaluation of most microbial soil communities by culture-independent techniques, i.e., without cultivation and multiplication in synthetic media, and has revealed a huge diversity of both culturable and unculturable bacteria and fungi, as well as the effects of diverse soil management strategies on this biodiversity (Hug et al. 2016, Jesus et al. 2009, Carvalho et al. 2016, Lucheta et al. 2017, Damian et al. 2021) . However, only culture-dependent techniques can provide the genetic resources that will be selected for use in sustainable management in agriculture, environmental quality, and food safety/security, and for other purposes.

The 2030 Agenda for Sustainable Development was adopted by UN Member States in September 2015. Soil biodiversity has a strong relationship to most of the 17 goals included in the Agenda. The soil processes of nutrient cycling, organic matter decomposition, soil organic matter dynamics, soil structure maintenance, and biological control are carried out by a vast array of organisms and directly linked to the provision of food, fiber, and fuel, carbon sequestration, water purification, and reduction in soil contamination.

Sustainability is based on increasing the contribution of soil biological processes in agricultural and forest systems, reducing the use of fertilizers and agrochemicals and, hence, their effects on greenhouse gas emissions, and increasing food safety/security and soil quality. Brazil has good practices in this direction described below.

In 2020, the Brazilian Ministry of Agriculture (Ministério da Agricultura, Pecuária e Abastecimento - MAPA) launched the National ¨Bio-inputs¨ Program (Programa Nacional de Bioinsumos), which aims to meet growing demand from the productive sector and society that seek alternatives for bio-based inputs in agricultural systems and increasingly sustainable products. Therefore, the general objective of the Program is to expand and strengthen the use of bio-inputs to promote the sustainable development of Brazilian agriculture and improve the quality and reliability of bio-inputs, meeting national and international market requirements. Bio-inputs are produced by dozens of factories dedicated to products for biological control and inoculants to promote plant growth, a growing market both in Brazil and in other countries that are increasingly concerned with food safety and environmental quality.

Biological pesticides

According to the Brazilian Association of Biological Control Companies (Associação Brasileira das Empresas de Controle Biológico), biological pesticides are already used on more than 23 Mha in Brazil, with growth estimates of up to 20% per year. The most expressive example is in sugarcane (*Saccharum officinarum*), where 5.2 million of hectares are treated with natural enemies of pests. *Cotesia flavipes* and *Trichogramma galloi* are used in the cultivation of sugarcane to control the sugarcane borer (*Diatraea saccharalis*). To control leafhoppers, *Mahanarva posticata* and *M. fimbriolata*, products formulated with the fungus *Metarhizium anisopliae* are applied. To control sugarcane weevils, the fungi *Beauveria bassiana* or *Metarhizium anisopliae* can be used as microbial biopesticides. Several commercial products are also available and registered in MAPA for applying at about 20 millions of hectares in many crops with *Bacillus thuringiensis*, *Beauveria bassiana*, *Metarhizium anisopliae*, *Baculovirus anticarsia*, and *Trichoderma harzianum*, among others, for controlling pests, diseases, and nematodes in various crops (Bettiol, 2011; Parra, 2014; Bueno et al. 2020).

Legume inoculants in Brazil: advances and challenges

A good example of soil process that can be managed to improve plant growth is symbiotic nitrogen fixation in legume species. Leguminosae is a diverse family with about 20,000 species worldwide. Leguminosae species predominate in most Brazilian biomes. In addition to the economic importance of these species, most of them are able to establish symbiotic relationships with N_2-fixing bacteria, commonly named “rhizobia”. Estimations are of at least 2,000 species in Brazil, most of them able to form symbiotic relationships with rhizobia (Moreira, 2006).

The most significant example of successful application of a biological process in Brazil and other Latin America countries, specifically Argentina and Uruguay, as well as United States, is the inoculation of selected *Bradyrhizobium* bacterial strains in the exotic species soybean, as a result of efforts made by Brazilian scientists since the 1960s (Franco, 2009). Application of soybean inoculants is increasing (*Figure 10*), reaching a total of about 64 million doses in 2018/2019 applied on an area of about 36 Mha, yielding 120 million tons of grain throughout Brazil (Conab, 2021). Inoculation of soybeans with selected *Bradyrhizobium* strains (approved by MAPA) (*Table 1*) totally replaces mineral N fertilizers, leading to savings of about 5 billion dollars this year (https://globalfert.com.br/outlook-globalfert-2020/). The N_2 fixed by Brazilian soybean in 2018/19 saved about 19 million tons of urea, which would represent about 130% of all N fertilizers consumed in Brazil, 88% of which were imported.

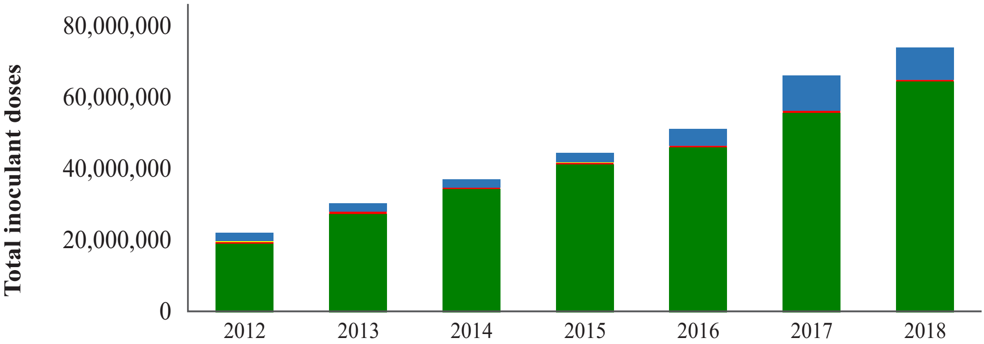
Table 1. Strains approved by the Minister of Agriculture, Supply and Livestock for some legume species

Legume species	Strains : SEMIA CODE (original code)	Identification
Glycine max (Soybean)	5019 (29 W),587, 5079 (CPAC15), 5080 (CPAC 7)	*Bradyrhizobium elkanii* (5079 & 587), *B. japonicum* and *B. diazoeficiens*
Phaseolus vulgaris (common-bean)	4077 (CIAT 899), 4088 (H 12), 4080 (PRF 81)	*Rhizobium tropici**, *R. Freirei**
Viga unguiculata (cowpea)	6461 (UFLA 03-84), 6463 (INPA 03-11B), 6462 (BR3267), 6464 (BR3262)	*Bradyrhizobium viridifuturi* symbiovar tropici*, *B.amazonense**,** *Bradyrhizobium yuanmingense,* *Bradyrhizobium pachyrhizi*
Acacia saligna *Chamaecrista ensiformis*	BR3804	*Mesorhizobium plurifarium**
Sesbania virgata	6402 (BR5404)	*Azorhizobium doebereinerae**
Stvlosanthes spp.	6154 (BR446)	*B. stylosanthis**
Centrosema spp.	690 (C100a)	*B. viridifuturi**
Neonatonia wightii (=Glycine wightii)	6149 (SMS 303)	*B. tropiciagri**
Desmodium ovalifolium (*=D. heterocarpon*)	6208 (CIAT 2372)	*B. embrapense*

*** New species, which description is based on isolates from Brazilian soils**
**** New species description submitted**

In addition to this enormous economic advantage, biological N_2 fixation from the air through *Bradyrhizobium* is a clean biotechnology, avoiding the lixiviation and volatilization of N compounds due to low N-fertilizer use-efficiency by plants. Unfortunately, soybean inoculation is currently the only success, because most inoculants produced by companies in Brazil are for soybean (*Figure 10*).

A decade ago, use of N_2-fixing bacterial strains in agriculture was almost exclusively restricted to soybean because, for a long time, it was believed that important crops such as cowpea (*Vigna unguiculata*) and common bean (*Phaseolus vulgaris*), mainly grown by small and medium farmers, would not respond to inoculation, due to their promiscuity with inefficient native rhizobia strains belonging to many species and genera. However, in recent years, use of inoculants containing efficient N_2-fixing bacterial strains has increased in these species. Although potential application is high, they have not benefitted as soybean has, even though Brazilian research institutions have strains selected for these crops and for about 100 other legume species (for forest, green manure, and forage species) (MAPA, 2011).



	2012	2013	2014	2015	2016	2017	2018
🟦 Others	2,575,227	2,148,788	2,254,986	2,874,619	4,597,753	9,710,256	9,169,169
🟨 Cowpea	180,914	239,260	46,524	96,259	67,624	94,730	66,288
🟥 Common-beans	270,448	477,848	339,340	403,820	377,563	658,603	279,948
🟩 Soybean	19,174,524	27,468,482	34,197,621	41,056,859	45,801780	55,215,175	63,945,667

Figure 10. Total inoculant doses sold according to crop from 2012 to 2018 (source: Associação Nacional de Produtores e Importadores de Inoculantes: http://www.anpii.org.br/)

Reasons for low adoption of N_2-fixing inoculants in other crop species compared to soybean are that soybean occupies large areas of Brazilian farmland and demands large amounts of inoculants, which is attractive to companies that produce them. These large farmers generally have consultants aware of the benefits of this biotechnology. Small and medium-sized farmers, who produce most of the food to supply the Brazilian population, do not know that this biotechnology exists. For the companies that produce these inoculants, it is more profitable to sell large amounts (wholesale) to large farmers than small amounts (retail) to small farmers. This is a typical example of the law of supply and demand, associated with lack of knowledge. Thus, effective communication channels must be established between scientists and social stakeholders directly linked with soil use and conservation. Biodiversity is of utmost importance to improve the contribution of symbiotic N_2 fixation in legume crops. Even soybean inoculation is being threatened by pressure from chemical fertilizer companies selling NPK formulas containing increased amounts of mineral N, which could lead to inhibition of biological N_2 fixation. Another threat is ¨on farm¨ production of inoculants produced without quality control, compromising a relatively well-established market of the certified inoculants. Nevertheless, the on-farm production of good quality inoculants and biopesticides may favor the expansion of the use of these bio-inputs to other species besides soybeans.

Multifunctional inoculants and co-inoculation of beneficial microbes

Researchers continue to select efficient N_2-fixing strains for important crops. Native soil communities occurring in Brazilian biomes such as the Amazon, Cerrado, and Atlantic Forest have been the sources of these genetic resources (Costa et al. 2020, Oliveira et al. 2020). In these studies, in recent years, researchers have considered rhizobia species as generally multifunctional.

In addition to biological N_2 fixation, they are able to perform diverse plant-growth-promoting processes, such as phosphate solubilization, phytohormone and siderophore production, and biological control of pests and diseases. Multifunctionality of plant-growth-promoting traits is also widespread in non-rhizobia plant-growth-promoting rhizobacteria (Oliveira-Longatti et al. 2014). Multifunctionality and co-inoculation of beneficial microbes represent potential windows of opportunity to explore for improving the contribution of biological processes in agroecosystems, as well as for increasing their use in other legume and non-legume species. Co-inoculation with *Azospirillum*, a non-symbiotic genus, is an increasing market for soybean, but also for inoculation in grasses such as maize, wheat, rice, and pasture species (*Figure 10*). The market for mycorrhizal fungi represents another window of opportunity, though not yet economically important and efficient, due to the widespread natural occurrence of these organisms and the lack of host specificity. However, stimulants of mycorrhization, such as formononetin, have proven to be a promising tool, especially in the event of low phosphorus inputs in soybean and maize (Ribeiro et al. 2016, Santos et al. 2020).

Concluding remarks

The immense biodiversity extant at the various types of Brazilian soils and climate conditions is a valuable source of genetic resources, with biotechnological potential that should also be considered in soil conservation programs. Brazilian diversity of many functional groups of soil organisms are still underestimated due to many reasons such as: the large size of the country territory with majority of areas with natural biomes with difficult access, low number of taxonomists, most surveys carried out in areas near research institutions. Despite of that, figures of native species already obtained are amazing: termites-300 (Constantino and Acioli, 2006), earthworms-253 (James and Brown, 2006) and dung beetles-726 (Vaz-de-Mello, 2021). Brazil also harbors 50% of all species of the world of the ubiquitous arbuscular mycorrizal fungi (Stürmer and Siqueira, 2006).

In Brazil, soil management systems under conservation agriculture have been evolving to increase plant diversity, and biotechnologies are already used on a large scale, especially for commodity crops such as soybean, sugarcane, and maize. However, the dissemination of biotechnologies, such as rhizobial inoculants, whose availability is still unknown to the vast majority of small and medium-sized farmers, who produce and conserve most edible species consumed by the Brazilian population, should be encouraged. Technologies that increase the growth and deeper penetration of plant roots in different crop systems should also be encouraged. An increase in the contribution of soil biological processes will be possible through more studies that reveal biodiversity and its functions and applications, as well as by increasing awareness of the role of biodiversity among the various social segments. Extension services and practices that popularize science should be increased to achieve this awareness. Knowledge of biodiversity is a strategic necessity from a political, economic, social, and environmental perspective. Effective communication between different sectors of society, government, and the scientific community must be established.

Literature

Alvim, R., Nair, P. K. R. (1986). Combination of cacao with other plantation crops:an agroforestry system in Southeast Bahia, Brazil. *Agroforestry System* **4** (1):3–15. https://doi.org/10.1007/BF01834698

Assis, P. C. R., Stone, L., F., Medeiros, J. C., Madari, B., E., Oliveira, J.de M. Wruck, F. J. (2015). Atributos físicos do solo em sistemas de integração lavoura-pecuária-floresta. *Revista Brasileira de Engenharia Agrícola e Ambiental* **19** (4): 309–316. doi: https://doi.org/10.1590/1807-1929/agriambi.v19n4p309-316

Balbino, L. C., Cordeiro, L. A. M., Porfírio-da-Silva, V., Moraes, A. de, Martínez, G. B., Alvarenga, R. C., Kichel, A. N., Fontaneli, R. S., Santos, H. P. dos, Franchini, J. C., Galerani, P. R. (2011). Evolução tecnológica e arranjos produtivos de sistemas de integração lavoura-pecuária-floresta no Brasil. *Pesquisa agropecuária brasileira* **46** (10): i-xii. doi: https://doi.org/10.1590/S0100-204X2011001000001

Bayer C., Dieckow J. Lessons Learnt from Long-term No-till Systems Regarding Soil Management in Humid Tropical and Subtropical Regions. In: Dang Y., Dalal R., Menzies N. Eds. No-till Farming Systems for Sustainable Agriculture. pp 437-457. Springer, Cham., 2020 https://doi.org/10.1007/978-3-030-46409-7_25.

Berendsen, R. L., Pieterse, C. M. J., Bakker, P. A. H. M. (2012). The rhizosphere microbiome and plant health. *Trends Plant Science* **17**: 478–486. https://doi.org/10.1016/j.tplants.2012.04.001

Bettiol, W. Biopesticides use and research in Brazil. (2011) *Outlooks on Pest Management* **22** (6): 280-283. https://doi.org/10.1564/22dec10

Bieluczyk, W., Piccolo, M.C., Pereira, M.G., Moraes, M. T., Soltangheisid, A., Bernardi, A.C.C., Pezzopane, J.R.M., Oliveira, P.P.A., Moreira, M.Z., Camargo, P.B., Dias, C.T.S, Batista, I., Cherubini, M.R. (2020). Integrated farming systems influence soil organic matter dynamics in southeastern Brazil. *Geoderma* **371**: 114368. https://doi.org/10.1016/j.geoderma.2020.114368

Bolliger A., Magid J., Amado T.J.C., Skóra Neto F., Ribeiro M.F.S., Calegari A., Ralisch R., Neergaard A. (2006). Taking stock of the Brazilian "zero-till revolution": a review of landmark research and farmers' practice. *Advances in Agronomy* **91**: 47–110. https://doi.org/10.1016/S0065-2113(06)91002-5.

Braga RF, Korasaki V, Audino LD, Louzada J. (2012). Are Dung Beetles Driving Dung-Fly Abundance in Traditional Agricultural Areas in the Amazon? *Ecosystems* **15**, pages1173–1181. DOI: https://doi.org/10.1007/s10021-012-9576-5

Brienza Junior, S.,Yared, J. A. G. (1991). Agroforestry systems as an ecological approach in the Brazilian Amazon development. *Forest Ecology and Management* **45** (1–4): 319–323. https://doi.org/10.1016/0378-1127(91)90226-L.

Bueno, V. H.P.; Parra, J, P.; Bettiol, W.; Van Lenteren, J. C. Biological Control in Brazil. In: Joop C. van Lenteren; Vanda H.P. Bueno; M. Gabriela Luna; Yelitza C. Colmenarez. (Org.). Biological Control in Latin America and the Caribbean: Its Rich History and Bright Future. 1ed.Wallingford: CAB International, Wallingford, Oxfordshire, UK, 2020, v. 1, p. 78-107.

Calegari A., Araujo A.G., Tiecher T., Bartz M.L.C., Lanillo R.F., Santos D.R., Capandeguy F., Zamora J.H., Jump J.R.B., Moriya K., Dabalá L., Cubilla L.E., Cubilla M.M., Carballal M., Trujillo R., Peiretti R., Derpsch R., Miguel S., Friedrich T. No-Till Farming Systems for Sustainable Agriculture in South America. In: Dang Y., Dalal R., Menzies N. Eds. pp 533-565 No-till Farming Systems for Sustainable Agriculture. Springer, Cham. 2020. https://doi.org/10.1007/978-3-030-46409-7_30.

Chang, S.X. and Cheng, Y. *Agroforestry Systems: The Role of Trees in Ecosystem Services—A Special Issue in Collaboration with the 4th World Congress on Agroforestry.* Basel, Switzerland. 2020. Doi: https://doi.org/10.3390/books978-3-03928-165-7

Conab. Companhia Nacional de Abastecimento: Portal de Informações Agropecuárias – Produção Agrícola – Safra – Série Histórica dos Grãos. 2021. Accessed at 04 May 2021: https://portaldeinformacoes.conab.gov.br/safra-serie-historica-graos.html.

Carvalho, T. S., Jesus, E. C., Barlow, J., Gardner, T. A., Soares, I. C., Tiedje, J. M., Moreira, F. M. S. (2016). Land use intensification in the humid tropics increased both alpha and beta diversity of soil bacteria. *Ecology* **97**: 2760-2771. https://doi.org/10.1002/ecy.1513

Constantino, R., Acioli, A.N.S. Termite diversity in Brazil (Insecta: Isoptera). In: Moreira, F.M.S, Siqueira, J.O., Brussaard, L. Eds. Soil biodiversity in Amazonian and other Brazilian ecosystems, pp. 117-128. Wallingford: CABI. 2006.

Cooper, H.V., Sjögersten, S., Lark, R.M., Girkin, N.T., Vane, C.H., Calonego, J.C., Rosolem, C., Mooney, S.J. (2021). Long-term zero-tillage enhances the protection of soil carbon in tropical agriculture. *European Journal of Soil Science Special* Issue: 1–16. https://doi.org/10.1111/ejss.13111

Costa, E. M, Ribeiro, P. R.A., Carvalho, T. S., Vicentin, R.P., Balsanelli, E., Maltempi E.S., Liesbeth, L., Willems, A., Moreira, F. M.S. (2020). Efficient Nitrogen-Fixing Bacteria Isolated from Soybean Nodules in the Semi-arid Region of Northeast Brazil are Classified as *Bradyrhizobium brasilense* (Symbiovar Sojae). *Current Microbiology* **77**: 1746-1755. https://doi.or/10.1007/s00284-020-01993-6

Damian, J. M., Da Silva Matos, E., Pedreira, B. C., De Faccio Carvalho, P. C., De Souza, A. J., Andreote, F. D., Premazzi, L. M., Cerri, C. E. P. (2021). Pastureland intensification and diversification in Brazil mediate soil bacterial community structure changes and soil C accumulation. *Applied Soil Ecology* **160**: 103858. https://doi.org/10.1016/j.apsoil.2020.103858

Dijkstra F. O solo ensinou: plantio direto, um caminho para o futuro. Ponta Grossa, Paraná. 2020 Inter Art Gráfica e Editora Ltda, 356p.

Donagemma, G. K., Freitas, P.L., Balieiro, F.C., Fontana, A., Spera, S. T., Lumbreas, J.F., Viana, J.H.M., Araújo Filho, J.C. de., Santos, F.C.dos, Albuquerque, M.R., Macedo, M.C.M., Teixeira, P.C., Amaral, A.J., Bortolon, E., Bortolon, L. (2016). Characterization, agricultural potential, and perspectives for the management of light soils in Brazil. *Pesquisa Agropecuária Brasileira, Brasília*, **51** (9): 1003-1020. https://doi.org/10.1590/S0100-204X2016000900001

FAO, Food and Agriculture Organization of the United Nations. Sete Lagoas consensus. *In*: FAO. An international consultation on integrated crop-livestock systems for development, Rome: FAO. 2010

FAO, ITPS, GSBI, SCBD and EC. 2020. State of knowledge of soil biodiversity - Status, challenges and potentialities, Report 2020. Rome, FAO. https://doi.org/10.4060/cb1928en

Food and Agriculture Organization (FAO), 2021. FAOSTAT Online Electronic. Accessed 05 May 2021 at: http://www.fao.org/faostat/en/#data/RFN.

Franco, A.A. (2009). Fixação Biológica De Nitrogênio Na Cultura Da Soja No Brasil: Uma Lição Para O Futuro (Biological Nitrogen Fixation in Soybean in Brazil: A Lesson for the Future). *Boletim da Sociedade Brasileira de Ciência do Solo* **34** (1):23-24.

Fávero, C., Lovo I. C., Sá Mendonça, E. (2008). Recuperação de área degradada com sistema agroflorestal no Vale do Rio Doce, Minas Gerais. *Revista Árvore* **32**: 861-868. doi: https://doi.org/10.1590/S0100-67622008000500011

Galdos, M.V., Pires, L.F., Cooper, H.V., Calonego, J.C., Rosolem, C.A., Mooney, S.J. (2019). Assessing the long-term effects of zero-tillage on the macroporosity of Brazilian soils using X-ray Computed Tomography. *Geoderma* **337**: 1126–1135. https://doi.org/10.1016/j.geoderma.2018.11.031

Gama-Rodrigues, E.F., Ramachandran Nair, P.K., Nair, V.D., Gama-Rodrigues, A.C., Baligar, V.C., Machado, R.C.T. (2010). Carbon Storage in Soil Size Fractions Under Two Cacao Agroforestry Systems in Bahia, Brazil. *Environmental Management* **45**: 274–283. https://doi.org/10.1007/s00267-009-9420-7

Hug, L. A, Baker, B.J., Anantharaman, Brown, C.T., Probst, A.J., Castelle, C.J., Butterfield, C.N., Hernsdorf, A.W., Amano, Y., Ise, K., Suzuki, Y., Dudek, N., Relman, D.A., K.,Finstad, K.M., Amundson, R.,Thomas, B.C., Banfield, J.F. (2016). A New View of The Tree of Life. *Nature Microbiology* 1: 16048 https://doi.org/10.1038/nmicrobiol.2016.48

IBGE. Instituto Brasileiro de Geografia e Estatística, 2019. Censo Agropecuário 2017: resultados definitivos. IBGE, Rio de Janeiro, v.8, p.1-105.

IUSS Working Group WRB (2015). World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome

Jagoret, P., Kwesseu, J., Messie, C., Michel-Dounias, I., Malézieux, E. (2014). Farmers' assessment of the use value of agrobiodiversity in complex cocoa agroforestry systems in central Cameroon. *Agroforestry Systems* **88**: 983–1000. https://doi.org/10.1007/s10457-014-9698-1.

James, S.W.; Brown, G. G. Earthworm Ecology and Biodiversity in Brazil. In: Moreira, F.M.S, Siqueira, J.O., Brussaard, L. Eds. Soil biodiversity in Amazonian and other Brazilian ecosystems, pp. 56-116. Wallingford: CABI. 2006.

Jesus, E. C., Marsh, T. L., Tiedje, J. M., James, M., Moreira, F. M. de S. (2009). Changes in land use alter the structure of bacterial communities in Western Amazon soils. *The Isme Journal* **3**: 1004-1011, 2009. https:// doi.org/10.1038/ismej.2009.47

Kämpf, N., Curi, N., Marques, J.J. Intemperismo e ocorrência de minerais no ambiente solo. In: Melo, V.F. and Alleoni, L.R.F. Eds. Química e mineralogia do solo. Parte I – Conceitos básicos. Sociedade Brasileira de Ciência do Solo. Viçosa-MG, 2016, p. 334-379.

Kichel, A.N., Costa, J.A.A., Almeida, R. G., Paulino, V. T. (2014). Sistemas de integração lavoura-pecuária-floresta (ILPF)- experiências no Brasil. *Boletim de Indústria Animal* **71** (1): 94-105.

Kou, Xinchang , Su, Tongqing , Ma, Ningning , Li, Qi , Wang, Peng , Wu, Zhengfang, Liang, Wenju. (2018) Soil micro-food web interactions and rhizosphere priming effect. *Plant and Soil* **432** (1-2), 129-142. https://doi.org/10.1007/s11104-018-3782-7

Lemaire, G., Franzluebbers, A., Carvalho, P. C. de F., Dedieu, B. (2014). Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agriculture Ecosystem Environment* **190**: 4-8. https://doi.org/10.1016/j.agee.2013.08.009

Lucheta, A. R., Cannavan, F. S., Tsai, S. M. , Kuramae, E. E. (2017). Soil fraction and black carbon particles of Amazonian dark earth harbor different fungal abundance and diversity. *Pedosphere* **27**: 832-845. https://doi.org/10.1016/S1002-0160(17)60415-6

MAPA-Ministério da Agricultura, Pecuária e Abastecimento. Acessed May 14th, 2021 at: *https://www.gov.br/agricultura/pt-br/assuntos/insumos-agropecuarios/insumos-agricolas/fertilizantes/legislacao/in-sda-13-de-24-03-2011-inoculantes.pdf/view.*

Martinelli, G. C., Schlindwein, M. M., Padovan, M., P., Vogel, E., Ruviaro C. F. (2019) Environmental performance of agroforestry systems in the Cerrado biome, Brazil. *World Development* **122**: 339-348

Matthews, R. B., van Noordwijk, M., Lambin, E., Meyfroidt, P., Gupta, J., Verchot, L., Hergoualc'h, K., Veldkamp, E. (2014). Implementing REDD + (Reducing Emissions from Deforestationand Degradation): Evidence on Governance, Evaluation and Impacts from the REDD-ALERT Project. *Mitigation and Adaptation Strategies for Global Change* **19** (6): 907–925. https://doi.org/10.1007/s11027-014-9578-z

Moraes, A., Carvalho, P.C.F., Anghinoni, I., Lustosac, S.B.C., Costa, S.E.V.G.A., Kunrathb, T.R. (2014). Integrated crop–livestock systems in the Brazilian subtropics. *European Journal of Agronomy* **57**: 4-9. https://doi.org/10.1016/j.eja.2013.10.004

Monroe, P. H. M., Gama-Rodrigues, E. F., Gama-Rodrigues, A. C., Marques, J. R. B. (2016). Soil carbon stocks and origin under different cacao agroforestry systems in Southern Bahia, Brazil. *Agriculture Ecosystem Environment* **221** (1): 99–108. https://doi.org/10.1016/j.agee.2016.01.022.

Moreira, F. M. S. Nitrogen- fixing Leguminosae nodulating bacteria. In: Moreira, F.M.S, Siqueira, J.O., Brussaard, L. Eds. Soil biodiversity in Amazonian and other Brazilian ecosystems, pp. 237-270. Wallingford: CABI. 2006.

Nair, P. K. R., Nair, V. D., Kumar, B. M., Showalter, J. M. (2010). Carbon sequestration in agroforestry systems. *Advances in Agronomy* **108**: 237-307. https://doi.org/10.1016/S0065-2113(10)08005-3.

Noda, S.N., Noda, H. Brocki, E. Percepção e Utilização da Flora nas Culturas Ticuna e Cocama na Microrregião do Alto Solimões, Estado do Amazonas, Brasil (Perception and Use of Flora in Ticuna and Cocama Cultures in the Alto Solimões Microregion, Amazonas State, Brazil.). In: Moreira, F. M. S., Siqueira, J. O., Brussaard, L. Eds. Biodiversidade do solo em ecossistemas brasileiros, pp. 43-65. Lavras: UFLA. 2008.

Oliveira, D. P., Soares, B. L., Ferreira, P. A. A., Passos, T. R., Silva, J. S., Ferreira, D. F., Andrade, M. J. B., Moreira, F. M.S. (2020) Selection of elite *Bradyrhizobium* strains by biometric techniques for inoculation in cowpea. *Soil Science Society Of America Journal* **84**: 1125-1138. 10.1002/saj2.20084

Oliveira-Longatti, S. M. De; Marra, L. M.; Soares, B. L.; Bomfeti, C. A.; Silva, K. Da; Ferreira, P. A. A.; Moreira, F. M. de S. (2014) Bacteria isolated from soils of the western Amazon and from rehabilitated bauxite-mining areas have potential as plant growth promoters. *World Journal of Microbiology and Biotechnology* **30**: 1239-1250. https://doi.org/10.1007/ s11274-013-1547-2.

Orgiazzi, A., Bardgett, R.D., Barrios, E., Behan-Pelletier, V., Briones, M.J.I., Chotte, J-L., De Deyn, G.B., Eggleton, P., Fierer, N., Fraser, T., Hedlund, K., Jeffery, S., Johnson, N.C., Jones, A., Kandeler, E., Kaneko, N., Lavelle, P., Lemanceau, P., Miko, L., Montanarella, L., Moreira, F.M.S., Ramirez, K.S., Scheu, S., Singh, B.K., Six, J., van der Putten, W.H., Wall, D.H. (Eds.), 2016, Global Soil Biodiversity Atlas. European Commission, Publications Office of the European Union, Luxembourg. 176 pp. https://op.europa.eu/en/publication-detail/-/publication/c54ece8e-1e4d-11e6-ba9a-01aa75ed71a1

Parra, J.R.P. (2014) Biological Control in Brazil: An overview. *Scientia Agricola* **71** (5): 345-355. http://dx.doi.org/10.1590/0103-9016-2014-0167

Ramos, H. M. N., Vasconcelos, S. S., Kato, O. R., Castellani, D. C. (2018). Above- and belowground carbon stocks of two organic, agroforestry-based oil palm production systems in eastern Amazonia. *Agroforestry Systems* **92** (2): 221–227. https://doi.org/10.1007/s10457-017-0131-4

Ribeiro, P. R. A., Santos, J. V., Carvalho, T. S., Silva, J. S., Resende, P. M., Moreira, F. M.S. (2016) Formononetin associated with phosphorus influences soybean symbiosis with mycorrhizal fungi and Bradyrhizobium. *Bioscience Journal* **32**: 940-951. 10.14393/BJ-V32N4A2016-32983 ctly.

Santos, H.G., Jacomine, P.K.T., Anjos, L.H.C., Oliveira, V.A., Lumbreras, J.F., Coelho, M.R., Almeida, J.A., Cunha, T.J.F., Oliveira, J.B. Sistema Brasileiro de Classificação de Solos. 5. Ed., rev. e ampl. Brasília, DF: Embrapa, Brasília, 2018.

Santos, J. V., Ribeiro, P.R.A., Carneiro, M. A. B., Soares, I. C., Fiorini, I. V.A., Cancellier, L. L., Veiga, A. D., Albuquerque, C. J. B., Pinho, R. G. V., Moreira, F.M.S. (2020) Formononetin accelerates mycorrhization and increases maize production at low phosphorus application rates. *Anais Da Academia Brasileira De Ciências* **92**: 1-14. https://doi.org/10.1590/0001-3765202020181371

Silva, F.A.M., Evangelista, B.A., Malaquias, J.V., Oliveira, A.D., Muller, A.G. (2017). Análise temporal de variáveis climáticas monitoradas entre 1974 e 2013 na estação principal da Embrapa Cerrados. Planaltina, DF: Embrapa Cerrados (Boletim de Pesquisa e Desenvolvimento 340).

Sisti, C.P.J., Dos Santos, H.P., Kohhann, R., Alves, B.J.R., Urquiaga, S., Boddey, R. M. (2004). Change in carbon and nitrogen stocks in soil under 13 years of conventional or zero tillage in southern Brazil. *Soil & Tillage Research* **76**: 39–58. https://doi.org/10.1016/j.still.2003.08.007

Souza, H. N., de Graaff, J., Pulleman, M. M. (2012). Strategies and economics of farming systems with coffee in the Atlantic Rainforest Biome. *Agroforestry Systems* **84** (2): 227–242. https://doi.org/10.1007/s10457-011-9452-x

Stieven, A.C., Oliveira, D.A., Santos, J.O., Wruck, F.J., Campos, D.T. da S. (2014). Impacts of integrated crop-livestockforest on microbiological indicators of soil. *Revista Brasileira de Ciências Agrárias* **9**: 53-58. 10.5039/agraria. v9i1a3525.Stürmer, S.L., Siqueira, J.O. Diversity of Arbuscular Mycorrhizal Fungi in Brazilian Ecosystems. In: Moreira, F.M.S, Siqueira, J.O., Brussaard, L. Eds. Soil biodiversity in Amazonian and other Brazilian ecosystems, pp. 206-236. Wallingford: CABI. 2006.

Uteau, D., Pagenkemper, S.K., Peth, S., Horn, R. (2013). Root and time dependent soil structure formation and its influence on gas transport in the subsoil. *Soil & Tillage Research* **132**: 69–76. http://dx.doi.org/10.1016/j.still.2013.05.001

Van Bruggen, A.H.C., He, M.M., Shin, K., Mai, V., Jeong, K.C., Finckh, M.R., Morris, J.G. Jr. (2018). Environmental and health effects of the herbicide glyphosate. *Science of the Total Environment* **616-617**: 255-268. 10.1016/j.scitotenv.2017.10.309

Vaz-de-Mello F. Z, Grossi 2021. Scarabaeidae in Catálogo Taxonômico da Fauna do Brasil. PNUD. Disponível em: <http://fauna.jbrj.gov.br/fauna/faunadobrasil/127498>. Acesso em: 20 Jun. 2021

Vinhal-Freitas, C., Wangen, D. R. B., Ferreira, A. de S., Corrêa, G. F., Wendling, B. (2010). Microbial and enzymatic activity in soil after organic composting. *Revista Brasileira de Ciência do Solo* **34**: 757-764. https://doi.org/10.1590/S0100-06832010000300017

Zago, L.M.S., Ramalho, W.P., Caramori, S. (2019). Does Crop-Livestock-Forest Systems Contribute to Soil Quality in Brazilian Savannas?. Floresta e Ambiente. 26 (3): e20180343. doi: https://doi.org/10.1590/2179-8087.034318