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Assessing soil degradation in Brazilian agriculture by a remote sensing approach to monitor bare soil frequency: impact on soil carbon

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ABSTRACT

In countries with extensive agricultural practices, there is a significant risk of soil degradation, making it essential to develop techniques for understanding and detecting these changes. In this study, we used an earth observation system to identify the temporal bare soil frequency and thus, relate it with soil tillage and its impact on soil carbon degradation. The work was performed in two important agricultural states of Brazil, São Paulo and Paraná. For that, historical field and Remote Sensing (RS) data were analyzed to identify the relation between bare soil areas and their degradation. The frequency of bare soil was detected by Landsat images, in the last 36 years using the Geospatial Soil Sensing System (GEOS3). Historical soil surface temperature data was produced using the same images. In addition, legacy pedological and crops (i.e., soil cover) maps were used. Finally, soil texture information was spatialized based on a synthetic soil image (SISY). A total of 28,000 sites with topsoil organic carbon (SOC) were used as the reference for degradation. The soils of the state of Paraná presented significantly lower bare soil areas when compared to the state of São Paulo, mainly due to the wide use of the No-Tillage system. The advancement of sugarcane harvesting technologies together with the "boom" of the commodities after 2000s was responsible for the considerable increases in soil cover conservation. It was noticed that the more exposed the soil remains, the less carbon it has, having a negative correlation ($r \approx -0.5$). Sandy soils in both states proved to be the ones that were subject to the highest exposure rates and thus, more degraded. This fact is of concern, given that sandy soils are more susceptible to degradation factors, such as erosion. We observed important historical public policies related to the temporal tillage systems adopted by agro-community, which had a significant impact on carbon dynamics. The remote technique was able to infer how the soil has been managed. This information is crucial as it provides a solid basis for developing future public policies aimed at sustainable production.

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1. Introduction

Soil constitutes a vital natural resource that sustains life on the planet and fosters socio-economic development. It provides several essential ecosystem services for various human activities, including the establishment of agroecosystems (Gomes et al., 2020). Despite this, intensive agricultural practices and farming have led to the degradation of the indicators of soil quality, resulting in decreased agricultural productivity and environmental degradation. Degraded lands can be defined as the physical-chemical and biological deterioration of the soil environment through anthropogenic activity, leading to a serious decline in soil volume, productivity, and fertility (Wang et al., 2023). One of the primary forms of soil degradation is erosion, primarily caused by land use beyond its capacity and inadequate management practices. These factors exacerbate the deterioration of soil quality indicators, ultimately resulting in decreased agricultural productivity and environmental degradation (Obalum et al., 2017). According to Imtiaz Rashid et al. (2016), unsustainable agricultural practice requiring land use and soil management were responsible for converting 30 % of the world's total cultivated land to degraded land by 2020.

Globally, Brazil has an important role in agricultural production and in the development of conservation methods for tropical soils (Fuentes-Llanillo et al., 2021). According to data from (MapBiomas, 2021), Brazil has a total of 264 million ha dedicated to agriculture, with 17.91 million ha located in São Paulo and 13.44 million ha in Paraná which raises the need for adequate soil condition monitoring, appropriate land use and soil management strategies. However, advancements in frontier agriculture challenge the ability to monitor soil health quality using traditional methods alone. This necessitates the integration of multiple technologies to identify critical areas that are more sensitive to degradation or are already experiencing some stage of soil degradation and, consequently, environmental degradation. (Gomes et al., 2019; Mello et al., 2023). Among the primary technologies recently employed to monitor soil condition and quality, RS techniques and their products stand out, particularly those associated with pedometric evaluation (Khosravi Aqdam et al., 2023a; Lehmann et al., 2020; Taiwo et al., 2023).

In a more recent development, the Intergovernmental Technical Panel on Soils (ITPS) has defined soil health as "the soil's capacity to uphold the productivity, diversity, and environmental benefits of terrestrial ecosystems" (FAO, 2020). Soil health derives from its favorable physical attributes (such as texture and water retention), chemical composition (including pH and soil organic matter and carbon), and biological characteristics (such as microbial diversity, nitrogen mineralization, and soil respiration). All these factors are crucial for fostering robust and fruitful crop production. In agricultural agroecosystems, soil health is often compromised by erosion, compaction, chemical contamination, and exposure to pollutants (Kibblewhite et al., 2007). These agro-environmental pressures lead to alterations in the soil's physical, chemical, and biological propertiescompromising its capacity to sustain plant and animal life (Bindraban et al., 2012). In this sense, some remote sensing (RS) techniques can detect and quantify some of the soil properties associated with altered SH-quality based on the SOC dynamics and management strategies.

Multiple studies have been conducted regarding soil degradation in the last decade with the use of remote sensing techniques (Anastopoulos et al., 2019). Gallo et al. (2022) using satellite images, developed a methodology for measuring soil loss through rainfall erosion in cultivated areas, identifying the inability of sugarcane straw to protect soil loss. Nascimento et al. (2021) detected soil degradation through temporal satellite images, finding a negative correlation between clay, cation exchange capacity (CEC) and organic matter (OM) with degradation and the degree of bare soil exposure. In addition, the Synthetical Soil Image (SySI), developed by (Demattê et al., 2020a,2020b), can be used as a tool to study soil exposure through pixels of the bands from Landsat satellite. The SySI information is a proxy that may refer to several soil characteristics such as texture, mineralogy, and carbon. Because of this, it can be used as an indicator for soil resource monitoring and analyzing the relationship between bare soil exposure and soil productivity (Denton et al., 2017).

Numerous studies have endeavoured to assess the spatial variability of soil health primarily by focusing on a single parameter, such as soil carbon (Minhoni et al., 2021; Tripathi and Tiwari, 2022), often without incorporating ground-truth indicators. The collection of a sufficiently representative number of soil samples poses a significant challenge to large-scale soil health assessment efforts (Khosravi Aqdam et al., 2023b). Additionally, laboratory analysis of soil samples is both expensive and time-intensive. Despite satellite images being widely available nowadays, there is a gap in knowledge regarding the identification of temporal soil exposure indices and their relationship with specific soil attributes related to soil health, such as soil texture, soil types, SOC content, soil management techniques, and land use and cover (Hurley and Nizzetto, 2018). Comprehending these relationships paves the way for the development of sustainable land-use practices and soil management strategies aimed at mitigating or preventing the adverse effects of soil degradation. By enhancing soil health and maximizing its potential productivity, these strategies contribute to overall environmental sustainability and agricultural resilience.

Based on the above, our objective was to evaluate how historical-temporal soil agricultural practices can, based on SOC dynamics, promote changes in soil quality, employing combined RS techniques. In addition, we aimed to discuss how these changes can constrain potential productivity in agricultural frontiers while safeguarding soil health. To achieve this, we utilized Synthetic Soil Images, Bare Soil Frequency Images, SOC content, soil texture, soil temperature, and soil types. This knowledge may inform the development of more efficient and sustainable land use and soil management strategies for sustainable agriculture.

2. Material and methods

2.1. Study area

The study area (Fig. 1) encompasses two important agricultural Brazilian states: Paraná and São Paulo. The state of Paraná, located in the southern region of Brazil, is characterized according to the Koppen classification, with 4 climatic classes: Aw, Cwa, Cfa and Cfb. In the Aw climate (humid tropical Cerrado), the dry season coincides with winter, with maximum rainfall in the dry months of less than 60 mm per month; The Cwa climate (humic temperate with dry winter), the summer is hot with air temperature above 22ºC in the hottest months and average precipitation below 60 mm in at least one of the months; Cfa (humid temperate with hot summer) and; Cfb (humid temperate with moderately hot summer) are oceanic climates without dry seasons (Alvares et al., 2013). The predominant soil type is primarily Ferralsols, 31 % (Bhering et al., 2013), followed by Nitisols, both with appropriate physical attributes favorable for agricultural activities (Fruett et al., 2022). On the other hand, the state of São Paulo, located in the southeastern region, has a tropical climate, characterized, following the Koppen methodology (Alvares et al., 2013), by having 4 climatic types, the same mentioned and explained for the State of Paraná (Aw, Cwa, Cfa) differing only in the Cwb type, characterized by a constant annual precipitation, without drought with the temperature of the hottest month above 22º and the temperatures of the coldest months ranging between −3 and 18ºC. This climate type is restricted to the coast of the state (De Souza Rolim et al., 2007). The predominant soil in São Paulo is Lixisols/Acrisols (Argissolos class in the Brazilian Soil Classification System (Safanelli et al., 2021), followed by Ferralsols, the two of them correspond to more than 80 % of the entire territory of the state (103.540,44 ha and 99.738,42 ha respectively) (Silva and Alvares, 2005).

Both the states Paraná and São Paulo encompass an area of approximately 350 million hectares, playing a crucial role in Brazilian agriculture, responsible for a significant production of crops such as

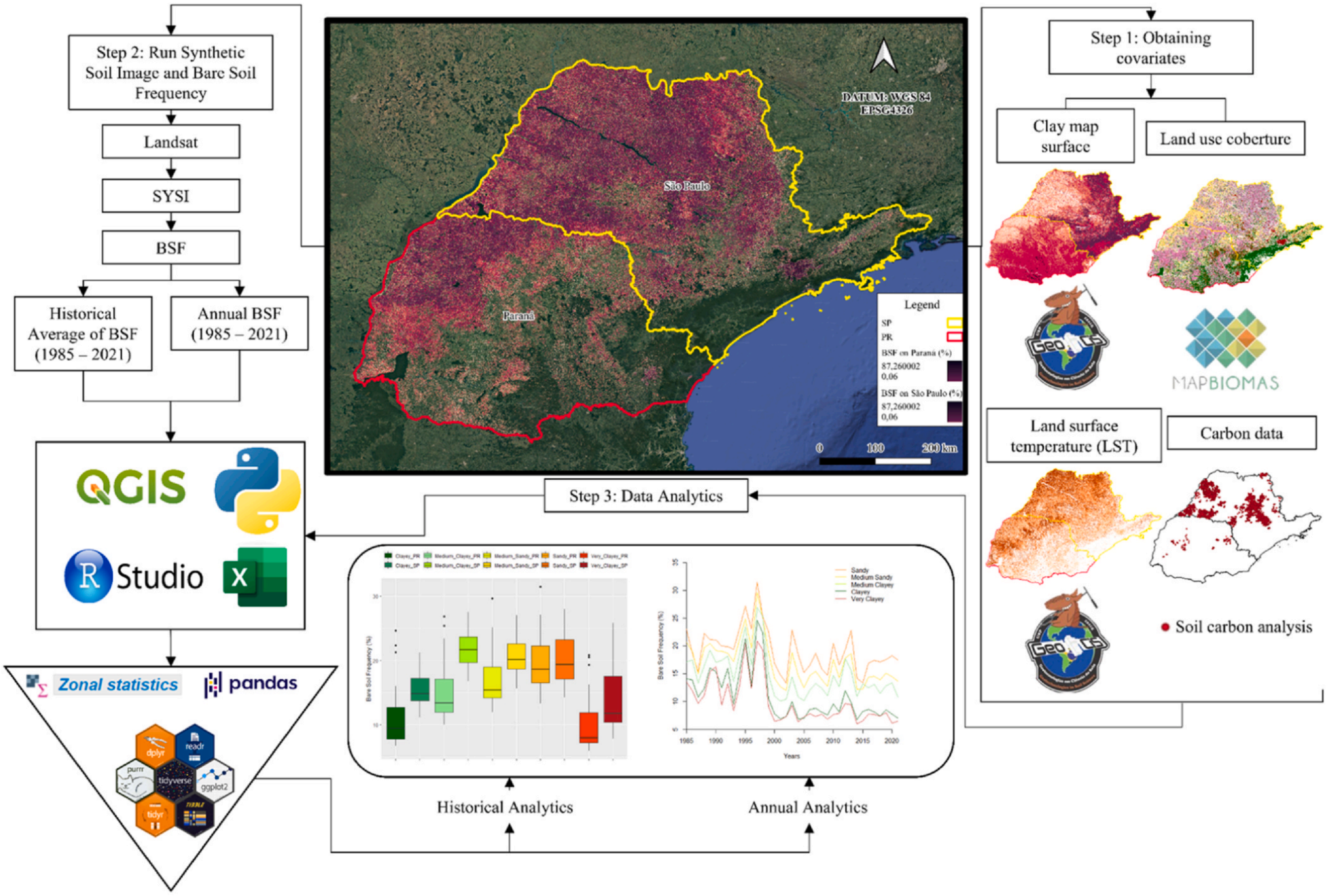

Fig. 1. Study area and mental model of methodology.

soybeans, corn, and wheat. Moreover, they are prominent regions that produce sugarcane, coffee, citrus fruits, and vegetables. The significance of these states in agriculture stems from their strategic location, suitable soil physical attributes, terrain conducive to mechanization, well-developed infrastructure, favorable climatic conditions, and vast areas of agricultural potential. These factors collectively contribute to the country's food supply.

2.2. Synthetic soil images (SySI) and Bare Soil Frequency (BSF) images

We created the SySI and BSF, following the GEOS 3 methodology, elaborated by Demattê et al. (2018) and Safanelli et al. (2020), with collections of Landsat 4–8 satellite images, from 1985 to 2021. The methodology of Safanelli et al. (2020) set rules to mask clouds, cloud shadows, photosynthetic vegetation and crop residues. The normalized difference vegetation index (NDVI) ranging from −0.15–0.20 was used to mask the vegetation present. And the normalized burn ratio 2 was used to mask crop residues, outside the range of −0.15 and 0.15. The raw bands from the satellite were also used in the classification, as the difference between bands 1 and 2 (B2 – B1) and bands 2 and 3 (B3 – B2). Some studies indicate that the discrimination of bare soil may be improved with the use of B1, B2 and B3 (Fiorio and Demattę, 2009; Nanni and Demattê, 2006). After the classification was made, the median reflectance of the soil surface was calculated to obtain a final reflectance value (2018,; 2020a,2020b). Finally, (Eq.1) using counting algorithms, the pixels of exposed soil were counted within an interval of images to obtain a frequency of exposed soil, represented by a percentage indicatingthe time the soil remained exposed (Nascimento et al., 2021)

$$BSF\,(\%) = \left(\frac{NPE}{NI}\right) \times 100 \tag{1}$$

Where,

BSF = Bare Soil Frequency; NPE = Number of times the pixel is exposed; NI = Number of images.

2.3. Temporal analysis of Bare Soil Frequency (BSF)

First, the annual BSF images were processed for the time interval proposed in the work methodology, 1985–2021 (named BSF_1985, BSF_1886, BSF_1987, ..., BSF_2021). For each year, the procedure is repeated, for example, in the 1985 BSF, all available images of that year were analyzed and the median soil exposure was calculated by acquiring the percentage of pixels exposure in that period. In this way, it is possible to make annual correlations and analyzes the frequency of exposed soil. In the same way, we have information for each year, and a BSF was calculated for the whole time interval so that correlations with static factors, such as soil texture, could be made.

The methodology on which the work is based on the use of multitemporal satellite images has been consolidated for years and has already become functional (Campos et al., 2022). Such images, both the SYSI and the BSF, were both prepared using the Google Earth Engine (GEE) platform, where it was possible to process and store the proposed data, in addition to providing the collection of the Landsat series of surface reflectance images from 1985 to 2019 (Landsat 4 Thematic Mapper (TM) (1985–1993), Landsat 5 TM (1985–2012), Landsat 7 Enhanced Thematic Mapper Plus (ETM+) (1999–2019) and Landsat 8 Operational Land Manager (OLI) (2013–2021).

Table 1
Description of covariates used in correlation studies.

Factor	Covariates	Unit	Reference
Soil Data	Clay map surface	g/kg	(Fongaro et al., 2018)
	Land use and land cover (LULC)	-	(MapBiomas, 2021)
	Land surface temperature (LST)	Kelvin	(Ermida et al., 2020)
	SOC	g/kg	GEOCIS

2.4. Statistical bare soil analysis

Zonal statistics algorithms, using the QGIS 3.28.5 software, were used to obtain the relationship between pixels from the annual BSF and the median of all years. With this tool, it is possible to calculate the value of one raster in relation to another one. This allows us to obtain the bare soil rate for each pedological, textural, land use, and cover class.

For the statistical analyses, some other methods were used, such as treating the carbon and BSF relationship in a general and specific way. First, a representative area was selected for each state where there was a high variability of soil exposure and points with observed values of soil carbon. With the specific areas delineated, the values of bare soil frequency for the points containing soil carbon content were extracted using the Point Sampling Tool in the QGIS 3.28.5 software. This methodology has already been consolidated in recent years with several works with similar analytical processes (Abdu et al., 2008; Chioderoli et al., 2012; Dieleman et al., 2013; Jeffery et al., 2011; Neina, 2019).

To understand the relation between soil carbon and the frequency of exposed soil, the historical BSF rasters were classified according to the quartile values, adapted from (Nascimento et al., 2022). Three levels of BSF was defined as low BSF (0–2.51 %), medium BSF (2.51 %-7.84 %) and high BSF (7.84–37.97 %).

With the quartiles established, the database containing points with soil carbon values was utilized to extract corresponding bare soil frequency values and soil types. Subsequently, the most prevalent crop for each point was determined by calculating usage and coverage modes. This process completed the compilation of information for the database.

2.5. Covariates

A variety of traditional and RS covariates were selected to understand the soil health status. Landsat 8 bands were used to obtain the Land Surface Temperature (LST) index. Clay mapping methodologies were used following approaches proposed by Fongaro et al. (2018) Historical land use and coverage were obtained from maps prepared by (MapBiomas, 2021). SOC (soil organic carbon) data were provided by the Geotechnologies in Soil Science Group (GEOCIS). Table 1

2.6. Topsoil clay texture map

The clay map of the topsoil layer (0–20 cm) was grouped according to their textural classes (Eq. 2) as developed by Fongaro et al. (2018). The research used the Temporal Synthetic Spectral (TESS) reflectance and Synthetic Soil Image (SYSI) (Demattê et al., 2018) methods to detect and describe textural spectral patterns on the image scale. A classification was made based on the clay content, in which 5 classes were described, very sandy, sandy, medium clayey, clayey and very clayey, following the rules described below.

2.7. Land use cover (LUC)

From the Mapbiomas collection 7 (MapBiomas, 2021), we acquired rasters of land use and coverage data from 1985 to 2021, with one image per year, developed by them. The pixels in these rasters were classified according to the vegetation cover. We used only land coverage data for Coffee, Pasture, Silviculture, Soybean and Sugarcane crops.

2.8. Land surface temperature (LST)

The Landsat 8 bands were used to obtain the Land Surface Temperature (LST) maps for each year of the time intervals proposed in the work and, a single image with the median for all 36 years. They were obtained with the Google Earth Engine Open- Source Code developed by Ermida et al., (2020).

2.9. Soil carbon data

The SOC data were provided by the Group in Geotechnology in Soil Science, GEOCIS (ESALQ - USP), which are composed of a set of 27.247 points of traditional soil analysis. The values were obtained in the laboratory using the calorimetry method, which proved to be efficient in measuring SOC (Fang et al., 2021).

3. Results and discussions

3.1. Historical Bare Soil Frequency

The Frequency of Bare Soil, between 1985 and 2021, (Fig. 2a) indicates the state of Paraná with lower soil exposure rates, presenting an average of 4 % less exposure for the entire interval and a maximum difference of 7.5 % in 1985. This indicates, a more efficient strategy (Fuentes-Llanillo et al., 2021) in terms of soil conservation than the State of São Paulo. Several exposure peaks are observed in Fig. 2a, and many of them can be explained by historical events. The 1990s were characterized by high political and economic instability in Brazil, with a great impact on agricultural production (Neri et al., 2000). In the early 1990s, with the beginning of Collor Government, the country was in a strong economic crisis and with policies to freeze expenses and increase taxes; with this, there was a significant drop in the 1991/1992 harvest (Pereira and Prado, 2002). Pereira and Prado (2002) showed that public policies created after Collor's impeachment encouraged farmer production, which ensured relatively controlled production until 1996. In 1997, agriculture had a drastic drop in its share of the national Gross Domestic Product (GDP), with 1996 being one of the years with the lowest investment in rural credit between 1985 and 1999 (Campos and Paula, 2002). José and Antunes (2021) highlighted 1997 as it was

$$\text{Soil textural class} \begin{cases} \text{-If clay contente is} < 15\% \\ \text{-If clay contente is} \geq 15\% \text{ and} \leq 25\% \\ \text{-If clay contente is} \geq 25\% \text{ and} \leq 35\% \\ \text{-If clay contente is} \geq 35\% \text{ and} \leq 60\% \\ \text{-If clay contente is} > 60\% \end{cases} = \begin{matrix} \text{-Sandy} \\ \text{-Medium Sandy} \\ \text{-Medium Clayey} \\ \text{-Clayey} \\ \text{-Very Clayey} \end{matrix} \tag{2}$$

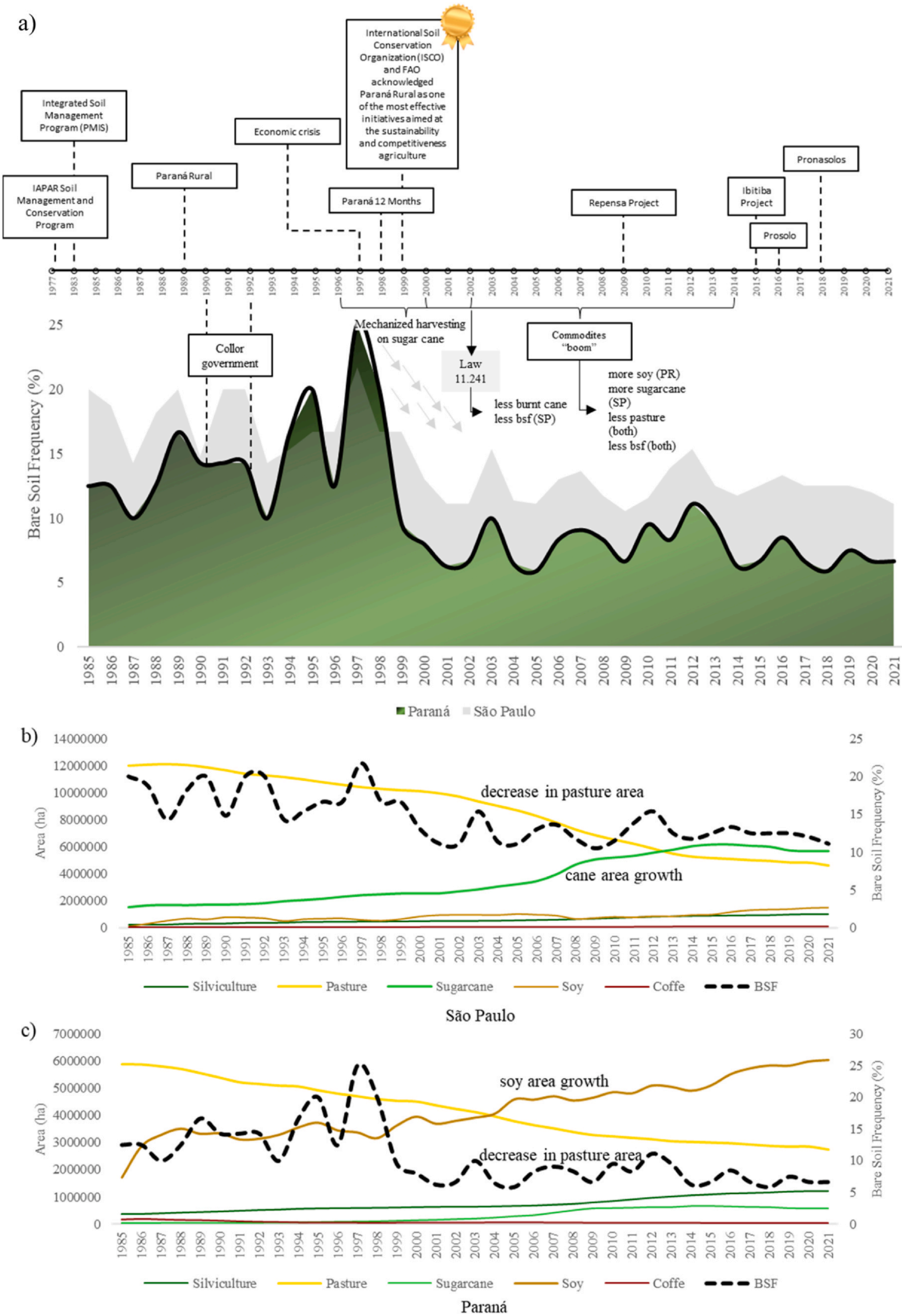

Fig. 2. Exposure rate of soils from Paraná and São Paulo (a). Increase of the agricultural areas of the cultures studied (b,c).

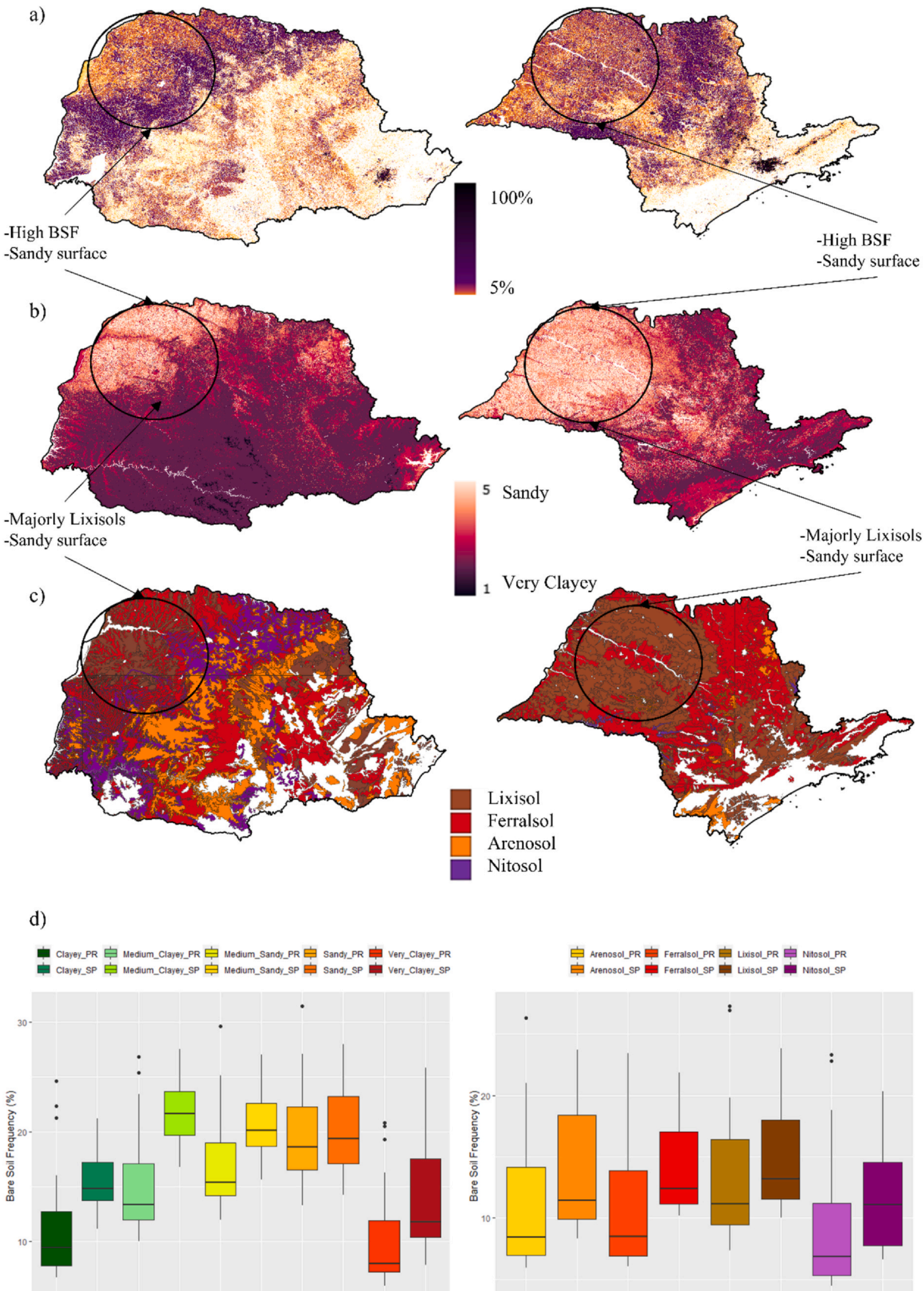

Fig. 3. Relationship between the frequency of exposed soil in the states of Paraná, left side and, São Paulo, right side (a), textural classes by state (b), soil exposure behavior by textural classes in both states (c) and boxplot relating all information (d).

the “Time of Crisis" where Brazil had the worst trade balance of the decade. Furthermore, in 1997, Brazil had the smallest agricultural trade balance in the last 40 years (Ramos et al., 2021). Such factors can justify the “boom” of exposed areas in 1997 (Fig. 2).

As shown in Fig. 2, it is possible to see that the end of the 1990s was characterized by a significant reduction in areas of bare soil. This factor is explained by a serious financial crisis in sugarcane production. This economic scenario led to a reduction in planting renewal and the crop was not harvested in some cases. These two points helped to reduce the number of areas of bare soil occupied by sugarcane cultivation (Campos et al., 2022).

Paraná historically had a lower bare soil rate than São Paulo (Fig. 2a). Paraná pioneered the no-tillage system in 1972 and its adoption is increasing until now (Carlos Henrique dos Santos Fernandes et al., 2019). This initiative was initially justified for the control of erosion and water runoff, however, later the efficiency of the system in the construction of healthy soil and the increase in productivity was evidenced (Possamai et al., 2022). According to a study carried out on the use of no-tillage system in Brazil, it was evident that, by the year 2017, it had a total of 33,052,971 ha cultivated under the no-tillage system, of which 4860,777 ha are in Paraná and 1004,735 ha in São Paulo (Fuentes-Llanillo et al., 2021). In addition, throughout Paraná's agricultural history, several initiatives were created to stimulate and encourage the continuity and growth of the use of soil management and conservation practices. The efficiency of the state of Paraná in soil management and conservation methods is evident when compared to São Paulo, mainly due to the higher adoption of the no-tillage system.

Between the mid-1990s and the beginning of the 2000s, it is possible to notice a drastic change in the concentration of bare soils (Fig. 2.). In this sense, some other historical events help to understand the BSF behavior of soils in both states. The sugarcane crop has undergone constant changes in its production chain over the years, mainly motivated by mechanized harvesting. This initiative began in 1996, with significant expansion in 2002 with the creation of Law 11,241, which prohibited the burning of sugarcane fields. In addition, in the early 2000s, the “commodity boom” began, thus increasing the growth of cultivated areas, mainly with soybeans and sugarcane (Campos et al., 2022).

3.2. Soil textural class and pedology

In both Paraná and São Paulo, areas characterized by sandy soils exhibited the highest BSF compared to clayey soils (Fig. 3.). These regions predominantly consist of Ferralsols with medium texture and/or Lixisols/Alisols featuring a surface horizon of sandy texture. The smooth relief in these areas facilitates agricultural mechanization operations and soil preparation management, thereby promoting growth in the BSF rate (Campos et al., 2022). Conversely, clay soils, including Ferralsols and Nitisols, whether associated with or without reliefs with steeper slopes, are more prone to compaction (Andognini et al., 2020; Hernández-Jiménez et al., 2017; Viciedo et al., 2018).

The results obtained and presented in Fig. 3(b, c) reveal a correlation between the Lixisols and sandy areas. This circumstance is elucidated by the presence of a textural gradient in Lixisols, that is, an A layer with lower clay content compared to the B horizon (Dengiz et al., 2018). Therefore, once the textural class map represents the topsoil layer, the relationship between Arenosols and sandy texture ceases to be an exclusive fact.

Soils with a sandy texture are the most fragile and exhibited the highest BSF values (Fig. 3). The heightened fragility of these soils primarily stems from their physical attributes such as small specific surface area (0.01–0.1 $m^2 g^{-1}$) and are poor in water and nutrient retention compared to high surface area clay particles (5–750 $m^2 g^{-1}$) (Troeh, 2005). According to Huang and Hartemink (2020), there is a directly proportional relationship between the amount of surface sand and the rate of soil loss. The sandier the soil is in its A horizon, the greater the tendency to suffer from erosion and leaching factors. Furthermore, the combination of these physical attributes makes it difficult to increase soil organic matter due to the lower capacity to form organometallic complexes and aggregation (Degens, 1967) and, low microbiota diversity compared to clayey soils, requiring greater vegetation cover and lower exposure rates so that their health is not compromised (Acosta-Martínez and Cotton, 2017).

On the other hand, Ferralsols and Nitisols showed the lowest BSF (Fig. 3d). These soils are characterized by the significant presence of clay oxides in their composition (WRS). Nascimento et al. (2022) noted that clayey soils are less susceptible to degradative factors caused by soil exposure than those caused by soil compaction. They elaborated a soil degradation index, in which the clay content was related to the levels of degradation. The levels vary from $< 12\%$ of clay (Very high level of degradation) to $> 40\%$ of clay (very low). In this sense, the Ferralsols and Nitisols, recurrent with a significant presence of clay, in the states of São Paulo and Paraná, show a good conservation trend. Nevertheless, much has been seen about the demystification of the direct relationship between productivity and soil texture. Studies have demonstrated that sandy soils can reach productivity levels similar to certain clayey soils, with the correct management (Bedin et al., 2003). This fact shows the importance of knowing about the functioning and proper management for each type of soil based on its texture, to achieve higher levels of productivity.

Historically, agriculture has been the main activity in the Northwest of Paraná, a factor that makes the highest BSF rates in this region evident (Fig. 3a). Until 1975, coffee production stood out and since then, soybean, corn, wheat and cotton have started to gain space, due to the climate crisis that hit coffee, leading to the technological intensification in the region (Serra, 2009). Sugarcane production also shows the highest growth rate in crops and agricultural productionwith the advance of mills in the Northwest region of the state (Santos and Araújo, 2014). Despite the high agricultural demand in the Northwest of the state, areas characterized by sandy texture, Paraná presents exemplary agricultural management, being a precursor and effective in the no-tillage system (Possamai et al., 2022).

The state of São Paulo was a Brazilian agricultural center, where an intense sugarcane expansion began in the last 30 years, presenting expressive rates of BSF in its entirety (Fig. 3d). In the first two decades of the 21st century, there was a decrease in pasture production of 53.5 % and an increase of 143.8 % in sugarcane fields (Ogura et al., 2022). However, soils cultivated exclusively for sugarcane production underwent significant physical alterations, such as changes in porosity and compaction, due to the use of heavy machinery. This compaction hampers water infiltration (Martinelli and Filoso, 2008). Moreover, the disintegration of loose materials and erosion contributed to the depletion of nutrients and carbon in the top layer of the soil, leading to decreased fertility and an increased reliance on chemical fertilizers (Borrelli et al., 2020). Furthermore, the monoculture of sugarcane has various environmental consequences, including soil and water contamination (both groundwater and freshwater) caused by the application of agrochemicals such as pesticides and fertilizers, eutrophication, high water consumption for irrigation, and atmospheric pollution resulting from burning practices (Bordonal et al., 2018). The fact that sugarcane production is the majority in the state, together with the high BSF of sandy soils, a scenario of potential damage to the health of soils in São Paulo is possible. This fact is observed in the high bare soil frequency compared with Paraná (Fig. 2). On the other hand, over the years, the cultivation of sugar cane has minimized its negative impacts on soil condition. Adopting various better management practices, including crop rotation, crop residue management, fertilization, by-product recycling, mechanized harvesting and carbon sequestration, allows sugarcane to impact ecosystems less detrimentally (Cherubin et al., 2021).

3.3. Land surface temperature behavior on bare soils

The surface temperature at the same location was higher where higher rates of bare soil frequency were observed. (Fig. 4a, b). Soil

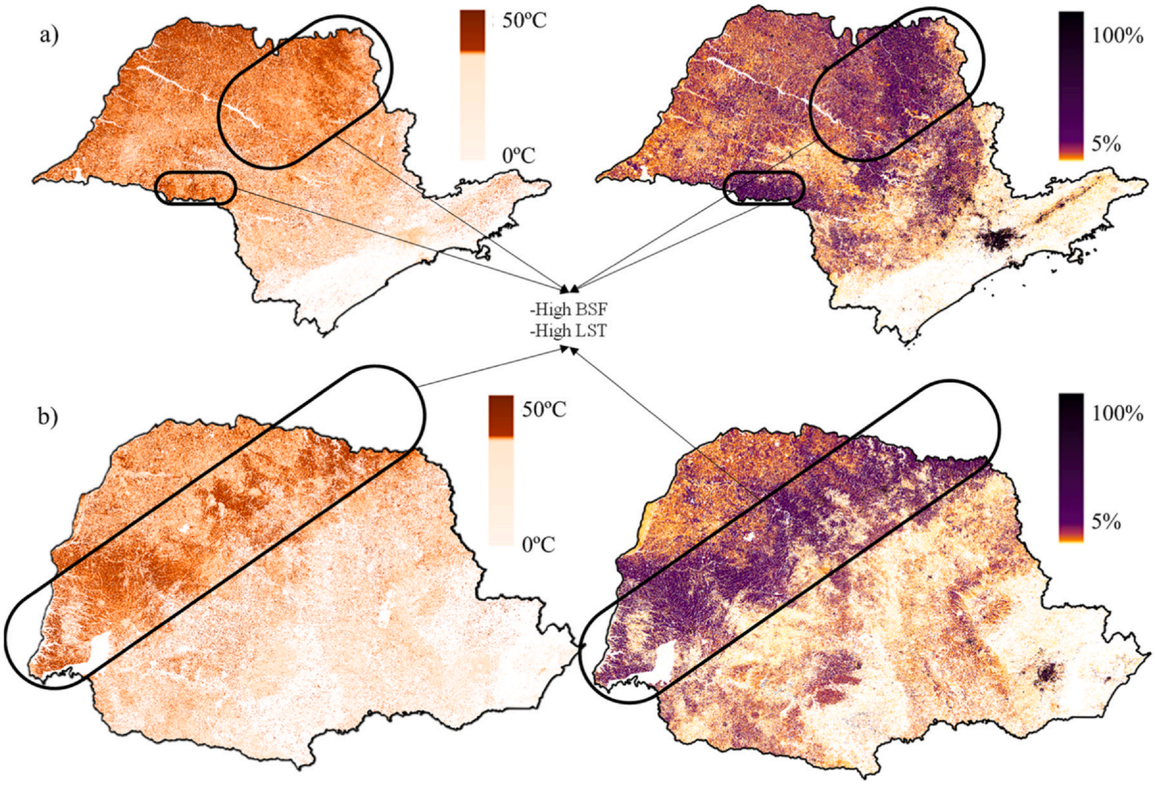

Fig. 4. Temporal analysis (1985–2021) of Bare Soil Frequency and Land Surface Temperature behavior. (a, b) - São Paulo and Paraná Land Surface Temperature and Bare Soil Frequency respectively.

temperature is responsible for regulating the physicochemical and biological processes of the soil, affecting the gas exchange processes between the atmosphere and the soil, influencing the dynamics of the decomposition of organic matter in the soil and its water content (Onwuka, 2016). Sayão et al. (2020) highlighted that bare soils have a higher surface temperature, and, in times of drought, this fact is even more present and relevant. York et al. (2000) reported soil temperature as one of the main factors that will define the successful growth of the plant present there. Probert (2000) showed the influence of soil temperature in root growth and seed germination. Sayão et al. (2020) further demonstrated that soil degradation has a direct relationship with intensive management and changes in surface temperature, reporting that with the consolidation of cultivation systems, periods of exposure of soils become more frequent.

3.4. Organic carbon in the soil and the impacts of land use and coverage on its dynamics

There is an inverse linear correlation between BSF and the SOC content, with a linear correlation (r) ranging from 0.43 to 0.5 (Fig. 5). This correlation indicates that as the BSF increases, the SOC content tends to decrease. This type of correlation arises from conventional soil preparation management techniques, which involve intensive disturbance through successive plowing and harrowing operations (Moussadek et al., 2014). These practices lead to increased soil aeration and temperature, along with the destruction of soil aggregates. As a result, physically protected organic matter becomes exposed to microbial attack, leading to the loss of total organic carbon COT and a reduction in the soil's capacity to sequester carbon (Topa et al., 2021) This process ultimately contributes to the deterioration of soil health. Furthermore, conventional soil preparation techniques exacerbate erosion, accelerate the mineralization of organic matter, and promote the oxidation of organic carbon in the soil. Additionally, they typically result in smaller amounts of organic inputs or more readily decomposed inputs than no-tillage techniques (Qi et al., 2021).

Several studies have shown a relationship between soil exposure and losses and gains in carbon contents (Abbas et al., 2020; Kern and Johnson, 1993; Ohiri and Ezumah, 1990; Senthilkumar et al., 2009).

Intensive agricultural practices are responsible for huge losses of SOC to the atmosphere. It is estimated that up to 60 % of the SOC in temperate regions and 75 % in the tropics has been lost due to poor soil management (Blanco-Canqui and Lal, 2008). Furthermore, in the same study, conducted an in-depth carbon content analysis experiment for several areas that differed in soil straw management, in which a significant difference was found in the carbon content only in the layer of the first 10 cm of soil, in-depth the difference was irrelevant. Complement to Blanco (2008) and Yang et al., (2013) showed that although the non-exposed soil system does indeed have its most diverse benefits, the highest C content in the soil surface cannot be exclusively attributed to no-tillage and the lowest levels to conventionally plowed soils. The surface loss could have been caused by erosion, and this “lost” carbon could have been deposited again on slopes. Denef et al. (2004) carried out a comprehensive study of the relationship between carbon sequestration in clayey soils under no-tillage system and conventional tillage conditions. In this study, a higher concentration of carbon was observed in the less bare soil frequency in relation to those that were more uncovered soils.

The primary land uses, and land cover associated with the highest BSF were the cultivation of sugar cane and soybeans in the states of São Paulo and Paraná, respectively (Fig. 6). These crops were predominantly cultivated on Nitisols and Ferralsols with a clayey texture. Both the land use and management strategies implemented in these areas for the indicated agricultural crops contribute to greater BSF and, consequently, negatively impact soil health. This is evidenced in our results by the decrease in SOC (Fig. 5). Although areas with clayey soils inherently provide greater chemical and physical protection for organic matter, the management practices adopted over decades for crops such as sugarcane and soybeans have led to the destruction of soil aggregates. This has significantly contributed to the degradation of organic matter in these soils.

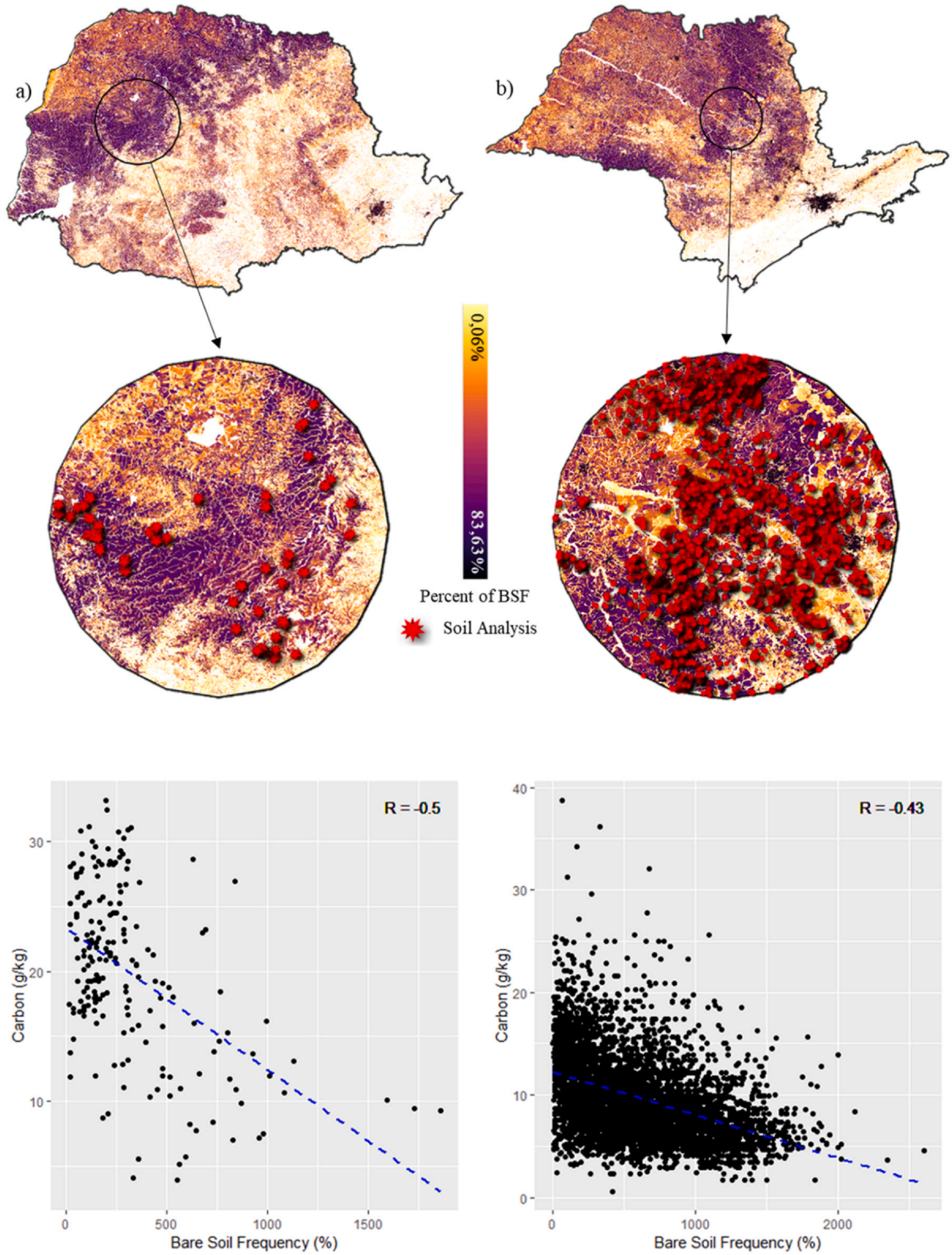

Fig. 5. Analysis of Linear Correlation between soil carbon content and Bare Soil Frequency in São Paulo and Paraná. (a, b) – Bare Soil Frequency in São Paulo and Paraná respectively; (c) – Linear correlation between BSF and SOC content in Paraná and São Paulo.

The expansion of the agricultural frontier and the consequent conversion of land cover threaten biodiversity, soil health, and water sources (Dalal and Lal, 2023). Studies show that the increase in soil surface temperature, aggravated by the transition from native vegetation to agriculture, negatively impacts the carbon stock of soils (Moisa et al., 2023). Additionally, the change in land use from native vegetation to arable land has reduced carbon stocks by up to 25 % under conventional planting (Dias et al., 2022). Sone et al. (2019) measured the effect of different land covers and land use on erosion and water infiltration in Argisols, finding that the conversion of natural vegetation to various land uses negatively impacts soil health, mainly through erosion and water dynamics. Furthermore, the economic impact of adopting conservation agriculture was estimated at 1.5 billion dollars, while the integration of crop-livestock-forest reached 5 billion dollars, highlighting the importance of proper and conservationist management to mitigate these effects (Polidoro et al., 2021).

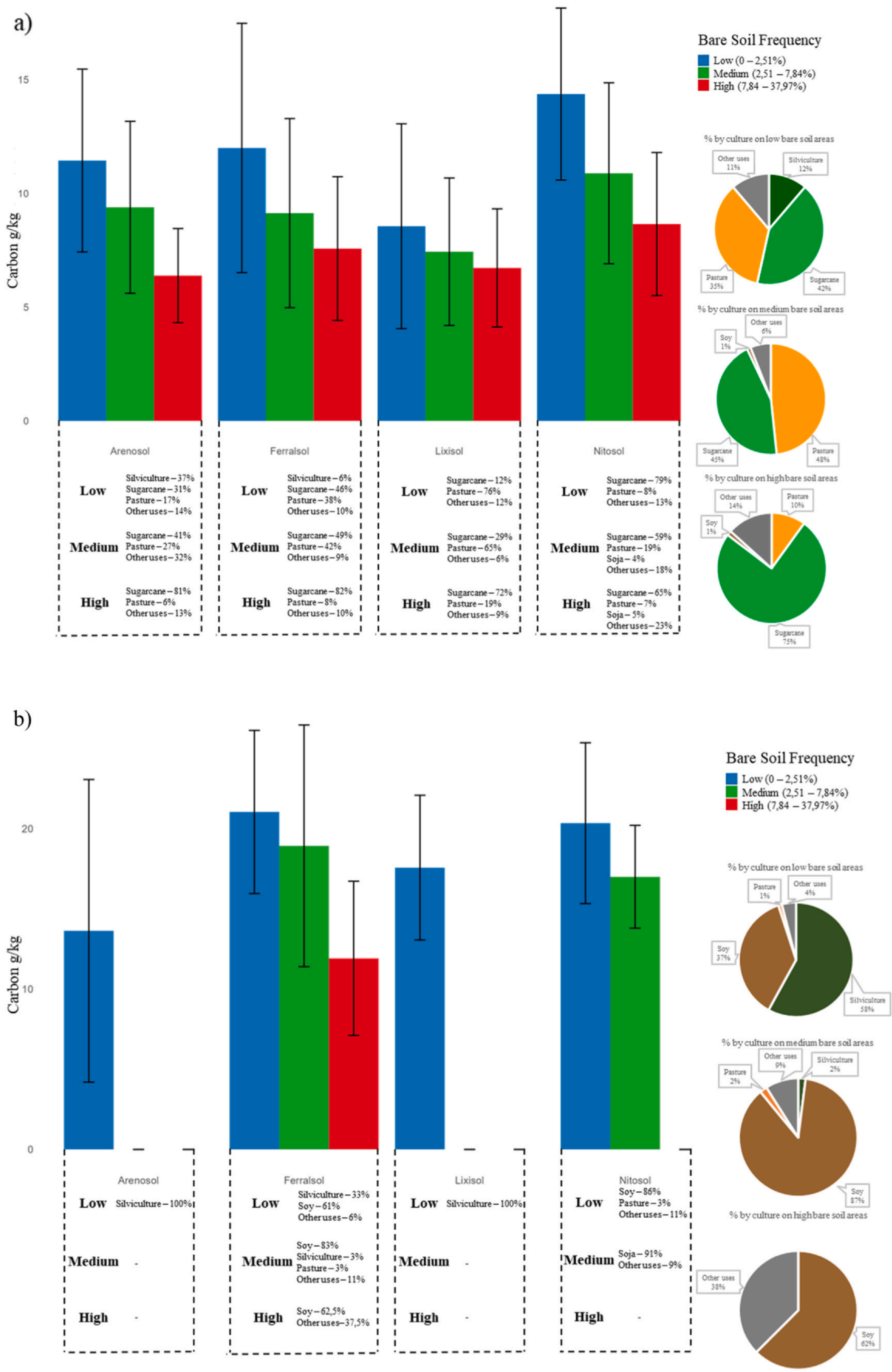

Fig. 6. Carbon content and use and occupation by exposure levels and soil classes in São Paulo (a) and Paraná (b).

4. Conclusion

The bare soil frequency (BSF) technique, based on spatial-temporal imagery coupled with SOC analysis, has proven to be a highly efficient combination for identifying areas where soils are particularly vulnerable to degradation. This innovative approach provided valuable information on the state of soils, clarifying the impact of different agricultural practices, and indicating a strong relationship with government public policies.

Using the BSF technique, we were able to detect areas characterized by direct planting and traditional tillage methods. Interestingly, we concluded that these sandy soils had higher FSB, making them more susceptible to risks of degradation and loss of productive potential. Through the BSF technique, we were able to detect areas characterized by non-tillage and traditional tillage methods. Interestingly, we conclude that those sandy soils exhibited a higher BSF, rendering them more susceptible to degradation risks and loss of potential productivity.

We found an inverse relationship between soil exposure and SOC. It became evident that as BSF increase, carbon levels decrease, with a correlation coefficient of -0.5 (r). This correlation underscores the importance of addressing soil management practices to safeguard carbon storage and, consequently, soil health.

The BSF technique offered us a unique opportunity to examine the historical evolution of soil management systems in large areas. By analyzing temporal data, we gained a comprehensive understanding of how these systems have evolved over time. This historical perspective has enriched the ongoing discourse on SOC, soil health, and degradation.

Our research takes on added significance when considering its implications for regions with substantial influence on Brazil's agricultural and economic landscape. Understanding the dynamics of soil exposure in such influential states can serve as a catalyst for a wide range of public initiatives. It also provides a solid foundation for critical analyses conducted by the general population and public policies.

CRediT authorship contribution statement

Jorge Rosas: Writing – review & editing, Writing – original draft. **Danilo Mello:** Writing – review & editing, Writing – original draft. **Nicolas Rosin:** Writing – review & editing. **Merilyn Amorim:** Writing – review & editing. **Bruno Bartsch:** Writing – review & editing. **Matheus Carraco Cardoso:** Writing – review & editing. **Sina Mallah:** Writing – review & editing. **Márcio Francelino:** Writing – review & editing. **Renan Falcioni:** Writing – review & editing. **Gabriel Sousa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marcelo Alves:** Writing – review & editing. **Jose Alexandre Melo Demattê:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Henrique Bellinaso:** Writing – review & editing, Writing – original draft.

Data availability

The data that has been used is confidential.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jose Alexandre Melo Dematte reports administrative support, article publishing charges, equipment, drugs, or supplies, statistical analysis, and writing assistance were provided by FAPESP. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Generative AI and AI-assisted technologies in the writing process

Statement: During the preparation of this work, the authors utilized GPT-4 to correct the grammar and structure of the English language, ensuring clarity in the sentences for the reader. After using this tool/service, the author reviewed and edited the content as needed and took full responsibility for the publication's content.

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