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Detection of bare soils in sugarcane areas by temporal satellite images: A monitoring technique for soil security

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A R T I C L E I N F O

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A B S T R A C T

Bare soil triggers several undesirable processes for its quality and remote sensing can be a powerful tool to monitoring its occurrence. This work aims to apply multi-temporal satellite image techniques to detect bare soil areas under sugarcane cultivation and relate with soil security. The study was carried out in an area of 2,574 km^2 located in Brazil. The MapBiomas land use and cover collection was used to know the sugarcane area changes from 1985 to 2019. A collection of Landsat images over 35 years (1985 to 2019) were used to create Synthetic Soil Images (SYSIs) and the Bare Soil Frequency Images (BSF) of the area. SYSIs were generated annually, in the rainy and dry season. BSFs was generated in the total period and every five years by dry and rainy season. Thus, the land use changes and bare soil occurrence were compared to categorical maps of soil types, surface clay classes and slope, and also with economic, social and political changes in the period. In general, the bare soil increased from 1985 to 2006, and began to decline thereafter because of "Agro-environmental Protocol' that anticipated the end of pre-harvest burning in sugarcane crop. BSF in the rainy season decreased over the period motivated by knowledge of farmers and changes in management. Despite this, many prone to erosion soils classes (Arenosols, Lixisols/Acrisols) remain under conventional tillage in the rainy season. We concluded that the use of multi-temporal satellite images is an important approach to monitoring soil management contributing to soil security.

1. Introduction

Sugarcane is cultivated in over 100 countries (Aparecido et al., 2021; Paungfoo-Lonhienne et al., 2021), on about 26 M ha (Dias et al., 2021b) and is one of the most important crops for the global economy (Arruda et al., 2021). In the actual global demand for renewable energy, where more than 64 countries have national programs to stimulate biofuels use (Caldarelli and Gilio, 2018), it is one of the most sustainable crops for biofuel production (Bordonal et al., 2018; Barbosa et al., 2019). Brazil is the largest sugarcane producer (Cherubin et al., 2021a; Marin et al., 2021), India, China, Thailand and Australia are other important producing countries (Han et al., 2022; Som-ard et al., 2021).

Brazil with approximately 376 sugarcane mills (Hernandes et al., 2021) is the second-largest bioethanol producer in the world (Carvalho et al., 2019; Gmach et al., 2021), producing 2348,591.8 thousand liters from sugarcane (CONAB, 2021). Ethanol is present in the consumer's daily life, mainly as a clean and renewable fuel (Coelho et al., 2006; Antunes et al., 2019), it begins in the 1970s, with the "Pro-Álcool" (Pro-Ethanol), the National Alcohol Program (Chavegatti-Gianotto et al., 2011) and nowadays, around 71.4% of vehicles are flex-fuel (Sindipeças and Abipeças, 2021). In addition, Brazil produces 29, 795.7 thousand tons of sugar (CONAB, 2021), around of 10% of national electricity demand (20 TWh of bioelectricity) is generate by co-generation (Gmach et al., 2020; Nechet et al., 2021) and sugarcane or its by-products have numerous other uses (Chavegatti-Gianotto et al., 2011; Dias et al., 2021b). Brazil has been grown sugarcane since the colonial period (Dias et al., 2021a), cultivating around 10 million ha mainly in two traditional regions: the center-south (92% of the

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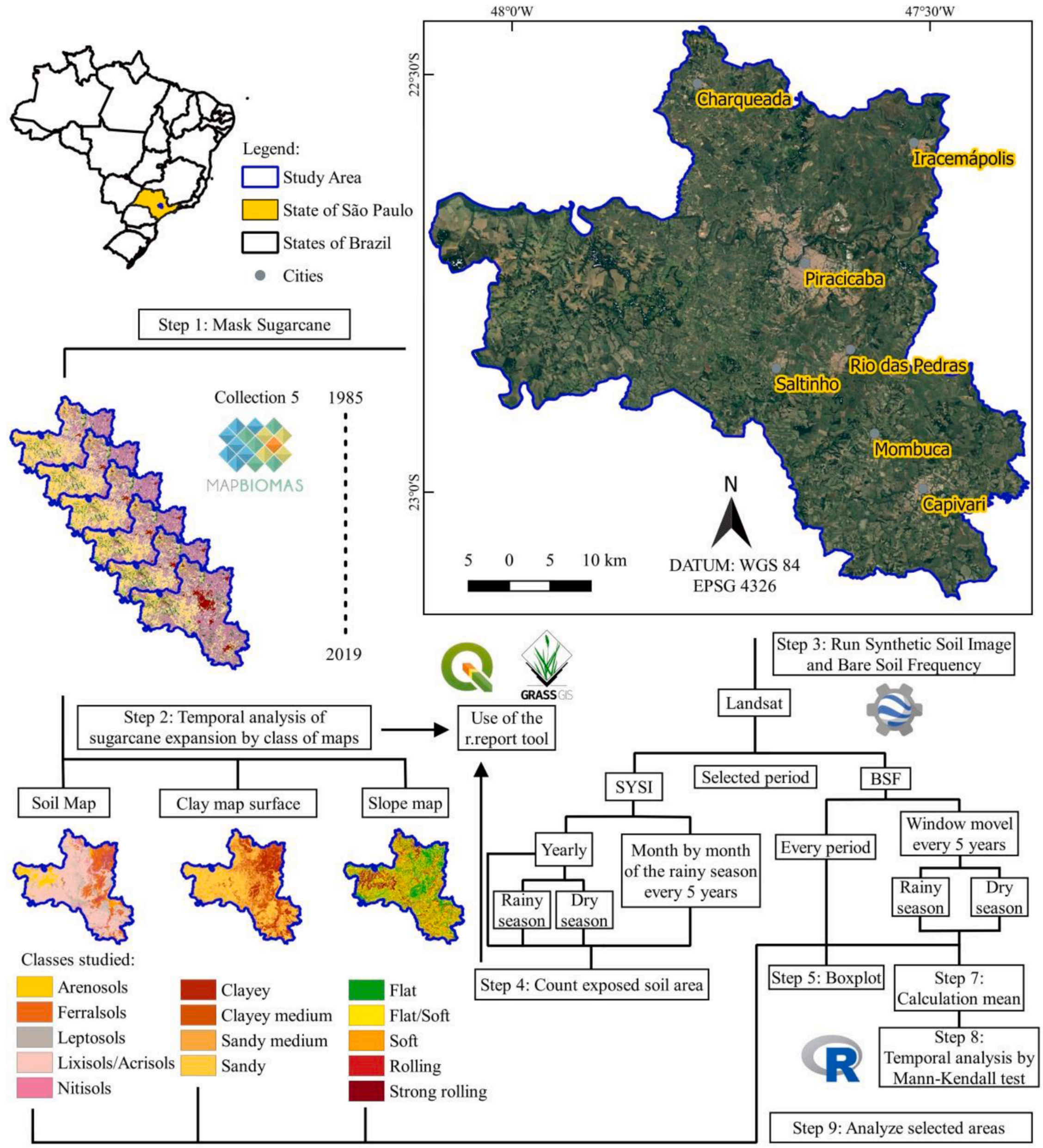

Fig. 1. Study area and flowchart of methodology.

production) and the northeast (Carvalho et al., 2019; Almeida et al., 2021; Cherubin et al., 2021b). In center-south region, São Paulo State concentrates 55% of sugarcane national production (Cherubin et al., 2021b; Teixeira et al., 2021; Valente e Laurini et al., 2021).

At the 21st Conference of the Parties (COP21), Brazil commits to reducing greenhouse gas emissions (Tenelli et al., 2019; Sanchez et al., 2021;). For this, it is estimated that the country will need to double the production of Ethanol by 2030 (Almeida et al., 2021; Silva et al., 2021) and increase the production of other bioenergy produced from sugarcane by-products (Silva et al., 2021; Dos Santos et al., 2022). To this end, the recent biofuel policy of the country, denominated "Renovabio" was created (Gonçalves et al., 2021; Grangeia et al., 2022).

Although sugarcane is considered a sustainable crop for biofuel production (Barbosa et al., 2019; Dos Santos et al., 2022) and its expansion in Brazil a solution to reduce CO_2 emissions (Jaiswal et al., 2017; Hernandes et al., 2021), some problems related to its soil management have been reported: degradation of the soil structure (Canisares et al., 2020), compaction (Esteban et al., 2019; Jimenez et al., 2021) excessive use of conventional tillage (Barbosa et al., 2019; Martini et al., 2021) and erosion (Medeiros et al., 2016). Soil erosion can cause lower sugar cane yield, due to diminishing the accumulation and transformation of soil organic matter (SOM), supply nutrients, infiltration, retention, and supply water (FAO and ITPS, 2015). In addition, carry sediment and nutrients to water bodies (Melland et al., 2022; Portinho et al., 2021; Santos et al., 2021). Keeping the soil uncovered (bare soil/ exposed soil) is considered one of the main causes of erosion (Morgan, 2005). The maintenance of soil cover (i.e. straw maintained in sugarcane areas) reduces soil erosion by dissipating the kinetic energy of raindrops, decreasing the flow velocity (Bordonal et al., 2018; Li et al., 2021) and reduces the pressure from agricultural machinery on the soil, attenuating the increase of compaction (Martini et al., 2021). Maintaining 50 and 100% of the sugarcane straw on the soil surface reduces soil erosion by 68 and 89% respectively (Martins Filho et al., 2009). Thus, efficient techniques are necessary for soil monitoring, preventing and minimizing soil threats and promoting soil security in sugarcane production.

The traditional ways of monitoring soil management are mostly through fieldwork (Oliveira et al., 1995; Ceddia et al., 1999; Prado and Centurion, 2001; Biddoccu et al., 2016), which are slow, and with low potential for spatial analysis. More recently, new techniques have emerged, like site-specific fertilizer management (Sanchez et al., 2021), kriging to map compaction areas (Arruda et al., 2021), magnetic susceptibility to create management zones (Catelan et al., 2022), among others (Almeida et al., 2021; Hernandes et al., 2021; Luciano et al., 2021; Som-ard et al., 2021). Another technique approach is to relate erosion susceptibility maps to land use (Azareh et al., 2019; Cerri et al., 2013; Krishna Bahadur, 2009; Weill and Sparovek, 2008). All of them do not include in their scope evaluate how many times the soil was bare in a certain period, a possible indication of potential degradation. Especially in agricultural areas where bare soils are related to management practices such as tillage (Demattê et al., 2018)

In this aspect, remote sensing (RS) is a powerful environmental monitoring technique (Ben-Dor et al., 2009; Aguiar et al., 2011; Som-ard et al., 2021). The RS is based in the interaction of electromagnetic energy with matter, for example soil (Chabrillat et al., 2019). Viscarra Rossel et al. (2016), present these relationships at the laboratory level, followed by Diek et al. (2016) at airplane level and finally at satellite level with (Mulder et al., 2011). All these researches prove the important relationship between the bare soil and the reflected energy, allowing, through multi-temporal images, to detect bare soil for multiples applications (Demattê et al., 2020; Minhoni et al., 2021). Therefore, the RS by multi-temporal strategies allows relating and evaluating the presence of bare soils with management aspects that can make it more prone to erosion or degradation (Nascimento et al., 2021). This work strategy for monitoring soil management is even more relevant in countries with large territorial extension and high agricultural demand, due to high costs (Dube et al., 2017).

Therefore, our hypothesis is: the use of multi-temporal satellite images makes it possible to evaluate aspects of soil management and their changes, in sugarcane areas, and to relate them to soil security, especially those linked to erosion. It is expected that: i) The expansion of sugarcane occurred mainly in soils more prone to erosion and was influenced by public policies and economic factors; ii) the amount of bare soils decreased after the implementation of the public environmental policy "Agro-environmental Protocol – Green Ethanol", which anticipated the end of sugarcane pre-harvest burning; iii) many areas with different levels of soil degradation propensity will be detected by satellite sensors during the crop field reform iv) Due to the expansion of sugarcane areas and crop management changes, there was an increase in bare soil areas in the rainy season

2. Material and methods

2.1. Study area

The study area (Fig. 1) has about 2574 km^2 and is located in the Piracicaba region, a traditional sugarcane production area, in São Paulo State, Brazil (Brinkman et al., 2018; Cervone et al., 2018). The region's climate, according to the Köppen system, is classified as Cwa, a Humid Subtropical with dry winter and hot summer, with rainfall in the driest month in the winter minor than 40 mm, temperature of the coldest month between −3 °C and 18 °C and temperature of the hottest month grater equal 22 °C (Alvares et al., 2013). Using climate data from the conventional meteorological station from the "Luiz de Queiroz College of Agriculture" (ESALQ/USP) from 1917 to 2021, we obtained that the mean annual precipitation is 1274 mm, being the wettest period (November to February) with a mean of 740 mm of rainfall and the driest period (June to August) with a mean of 102 mm of rainfall. The mean annual temperature is 21.7 °C. The mean temperature of the coldest month (July) is 17.6° C and of the hottest month is 24.8 (February).

The predominant soils of the region are Lixisols/Acrisols (~58%), Ferralsols (~19%), Leptosols (~13%) and Arenosols (~6%) with occurrence also of Cambisols, Nitisols and Gleysols (Oliveira et al., 1989).

2.2. Sugarcane crop management in study area

Sugarcane is a semi-perennial crop, harvested annually during an average of five years before replanting (Aguiar et al., 2011; Cheavegatti-Gianotto et al., 2011). The harvest season occurs from April to December (Dias and Sentelhas, 2017; Marin et al., 2021) (Fig. S1). The traditional period of sugarcane renewal (replanting) is carried out during two seasons in the center-south region, during February to April and September to November, being called "one year-and-half cane" or "18 months- cane", and "one-year cane" or "12 months-cane", respectively (Pagani et al., 2017). However, currently, with the increase of production areas and the longer period of harvests, sugarcane is planted throughout all year, thus, the terms "winter cane", and "two-summers cane" were created for sugarcane areas planted between May to August and December to January, respectively (De Maria et al., 2016). However, in center-south region, planting carried out in January can be incorporated into the 18 months-cane system (De Maria et al., 2016) (Fig. S2). Soil preparation (tillage) practices are performed only in replanting period (Barbosa et al., 2018), usually a conventional tillage (Cheavegatti-Gianotto et al., 2011; Barbosa et al., 2018). More details about the crop's production system in the center-south region are described by Aguiar et al. (2011) and Cheavegatti-Gianotto et al. (2011).

2.3. Identification of sugarcane expansion

The identification of sugarcane cultivation areas from 1985 to 2019 was carried out using the annual land use and land cover classification maps available in Collection 5 of the Annual Use and Coverage Mapping Project of the Earth in Brazil - MapBiomas (MapBiomas, 2021). The maps with a spatial resolution of 30 m were used to select only areas with sugarcane and mask out other land uses/covers from the images. Finally, the sugarcane areas were separated into soil, granulometric and slope classes.

For it, we used a soil legacy map produced by Oliveira et al. (1989) (scale of 1: 100,000) rasterized by Mendes et al. (2021), with a spatial resolution of 30 m to select the main soil orders used for sugarcane cultivation. Therefore, soil orders found were Argissolos, Latossolos, Neossolos Litólicos, Neossolos Quartzarênicos, and Nitossolos (Santos, 2018), which are equivalent to Lixisols/Acrisols, Ferralsols, Leptosols, Arenosols, and Nitisols (IUSS Working Group WRB, 2015), respectively. The soil clay content map (0–20 cm) was also obtained from Mendes et al. (2021) and classified into five granulometric classes, usually used for sugarcane soil management in São Paulo State (Bellinaso et al., 2021), as followed: sandy (<150 g kg^{-1}), medium-sandy (≥150 g kg^{-1} to <250 g kg^{-1}), medium-clay (≥250 g kg^{-1} to <350 g kg^{-1}) and clayey (≥350 g kg^{-1}). The slope map was obtained from the Shuttle Radar Topography Mission (SRTM) digital elevation model, using the algorithm proposed by Safanelli et al. (2020a) in the Google Earth Engine (Gorelick et al., 2017). Based on the slope values used for definition of soil conservation practices in sugarcane cultivation adopted in most of the center-south region, such as definition of the types of terraces used (Donzelli et al., 2018; Rotta and Zuquette, 2021) (Fig. S3), as well as the maximum slopes recommended for mechanized harvesting (15–17%) (Cheavegatti-Gianotto et al., 2011) and the characteristics of the study area (Sparovek and Schug, 2001; Pinto et al., 2003), the slope was classified as: flat (<6%), flat/soft (≥6% and <10%), soft (≥10% and <15%), rolling (≥15% and <20%) and strong rolling (≥20%).

2.4. Synthetic soil images and bare soil frequency images

We used a time series of satellite images from the Landsat 4 to 8 and the Geospatial Soil Sensing System (GEOS3) method, described in detail by Demattê et al. (2018) and Demattê et al. (2020), to obtain images of bare soil, called Synthetic Soil Images (SYSI) and images with the frequency of pixels with bare soil, called Bare Soil Frequency (BSF) in a pre-determined period between 1985 and 2019 (Fig. 1) (i.e.: from 1985 to 2019, or from 1985 to 1989, or from January to December in a specific year, or from all January months from 1985 to 1989, etc.). For each chosen time interval a specific SYSI was created. To identify bare soil pixels from single satellite images, a set of rules were used based in spectral indices. These rules, coupled with quality assessment bands, removed cloud, cloud shadow, inland water, photosynthetic vegetation, and non-photosynthetic vegetation (crop residues) (Safanelli et al., 2020b). Each pixel was classified as soil based on spectral indices: The Normalized Difference Vegetation Index (NDVI), with a threshold between −0.15 and 0.20 to mask out green vegetation, Normalized Burning Ratio (NBR2), with $a - 0.15$ and 0.15 to mask out crop residues, difference between bands 1 and 2 (B2 – B1) and bands 2 and 3 (B3 – B2) (Demattê et al., 2020, 2018). Afterwards, the bare soil pixels were used to calculate, pixel-by-pixel, the median values of topsoil reflectance for single bands and obtain the final reflectance value (Demattê et al., 2020; Demattê et al., 2018). In addition, bare soil pixels within the time-series determined, were counted to create bare soil frequency image, representing the times that the soil was bare (Nascimento et al., 2021). SYSI had 30 m spatial resolution and six spectral bands harmonized as blue (0.45 - 0.52 μm), green (0.52 - 0.60 μm), red (0.63 - 0.69 μm), near-infrared (0.76 - 0.90 μm), short-wave infrared 1 (1.55 - 1.75 μm) and short-wave infrared 2 (2.08 - 2.35 μm).

First, we obtained annual SYSIs from 1985 to 2019 (called SYSI_1985, SYSI_1986, …, SYSI_2019). For example, the SYSI_1985, is a Synthetic Soil Image created using bare soil pixels from Landsat images obtained between January 1, 1985 and December 31, 1985. A second step was to obtain annual SYSIs of specific periods classified as wet and dry seasons. We consider the four months with the highest historical average of rainfall as the rainy season (November to February) and the three months with the lowest historical average of rainfall (June to August) as the dry season. For example, the SYSI of wet season of 1990 (called SYSI_1990wet), is a SYSI created using bare soil pixels from Landsat images obtained in the months of January, February, November and December of 1990.

Finally, to assess whether there was an increase in the area of bare soil in the rainy season between 1985 and 2019, SYSIs were created for the months of November, December, January and February. As the rainy season corresponds to the period of greatest presence of clouds, which makes it difficult to detect bare soil pixels, these SYSIs were created for a period of five years (1985–1989, 1990–1994, 1995–1999, 2000–2004, 2005–2009, 2010–2014, 2015–2019) to minimize annual variations, reducing the effect of possible extreme years. In addition, this 5-year interval was chosen because it corresponds to the average period of crop replanting (Section 2.2) and it has been used in other sugarcane crop monitoring studies (Aguiar et al., 2011). For example, the SYSI of January from 1985 to 1989 (Called SYSI_Jan_19,851,989), is a SYSI created using bare soil pixels from Landsat images obtained in the months of January 1985, January 1986, January 1987, January 1988 and January 1989, a similar approach was taken by Mzid et al. (2021), to create an average bare soil frequency image for the month of September across years 2016 and 2019.

The acquisition and use of bare soil images obtained by multi-temporal satellite images has been consolidated in recent years, varying only in some methodological aspects of acquisition (Shabou et al., 2015; Diek et al., 2017; Demattê et al., 2018; Fongaro et al., 2018; Rogge et al., 2018; Loiseau et al., 2019; Roberts et al., 2019; Demattê et al., 2020; Poppiel et al., 2020; Gasmi et al., 2021; Safanelli et al., 2020b; Silvero et al., 2021a; Tziolas et al., 2020). However, obtaining and using them in different periods within a certain time interval (as proposed in this work) was only addressed by Zepp et al. (2021) that generated bare soil masks covering Germany for seven time periods from 1984 to 2019.

Although the BSF is an image that represents how many times a single pixel was bare soil in a determined period. The calculation of the BSF, according to Demattê et al. (2020), is obtained by dividing the number of pixels classified as bare soil by the number of the same pixels with valid information, i.e., pixels that have clouds, shadows, or inconsistent values are masked (excluded) in the calculation. First, to relate the frequency of bare soil and classes of the thematic maps, we use the previous time series of Landsat images to create a BSF image of the period from 1985 to 2019. In addition, to analyze trends of increase or decrease of bare soil in specific periods (rainy and dry seasons described above), we also obtained BSF images by the 5-year moving count of bare soil pixels, that is, counting the bare pixels every 5-year + 1. For instance, the BSF for dry season of the year 1989 was obtained using images from the months of June, July, August and September of years 1985 to 1989, and the BSF for dry season of the year 1990 from images from the months of June, July, August and September of years 1986 to 1990.

The most used methodologies for creating bare soil images mentioned above also generate BSF images (Demattê et al., 2018; Rogge et al., 2018). However, there are still few works that have used this resource to monitor and analyze the frequency of bare soil (Demattê et al., 2018; Demattê et al., 2020; Mzid et al., 2021).

Both the BSF images and the SYSIs were generated using the Google Earth Engine (GEE) cloud platform (Gorelick et al., 2017), which provided the processing structure and the Landsat series collection 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 the Landsat 8 Operational Land Manager (OLI) (2013–2019).

2.5. Data analysis

2.5.1. Land use and bare soil areas

Initially the areas of sugarcane, pasture and mosaic of agriculture and pasture classes were calculated, for each year from 1985 to 2019, using the Collection 5 of the Annual Use and Coverage Mapping Project of the Earth in Brazil - MapBiomas (MapBiomas, 2021). In a second moment, the sugarcane annual area (1985 to 2019) was calculated for each class of each thematic map (Soil, Granulometry and Relief). Using each annual SYSI and the map of sugarcane areas for the same year, the area of bare soil in the sugarcane crop for each year was calculated. With this information, the percentage of bare soil areas in the sugarcane areas was calculated for each year. The same approach was carried out with the rainy and dry period SYSIs from 1985 to 2019 and in the SYSIs of de wet season months from periods of five years. To perform the sum of these areas, the *r.report* tool present in the Qgis 3.16.10 software was used.

2.5.2. Bare soil frequency and thematic map classes

Using the BSF image from 1985 to 2019 and the Soil, Granulometric Classes and Relief maps, boxplots were obtained using the *ggplot2* package in R software (Wickham, 2016). In addition, a Pearson correlation test was performed between BSF values and clay content and slope, for which the *corrplot* package in R software was used (Wei and Simko, 2021).

2.5.3. Temporal analysis of the bare soil frequency

We calculate the mean value of BSF from 1989 to 2019, for each class of each thematic map, using the BSF images obtained by the 5-year window moving count for the two periods, the wet and the dry seasons. The 5-year window was chosen for the same reasons as described above (Section 2.4). To obtain the mean values we used the *zonal statistics tool of the raster layer* present in the Qgis 3.16.10 software. Then, we submitted the time series to the test of tendency of Mann-Kendall (MK) (Kendall, 1975; Mann, 1945). The test defines if a variable consistently changes through time or has an increasing or decreasing

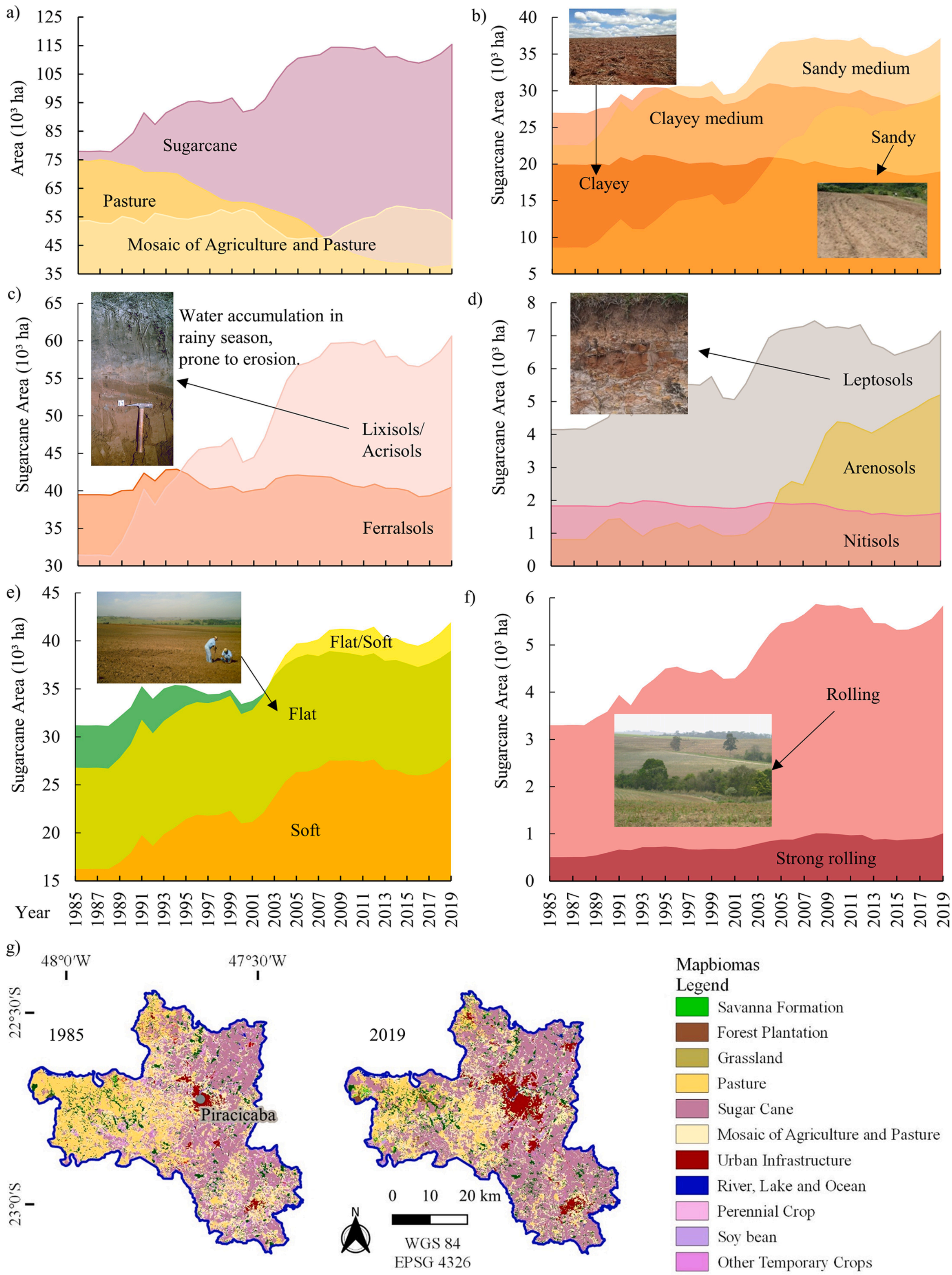

Fig. 2. Area of the main land use classes from 1985 to 2019 (a); sugarcane cultivation area in clay (b), soil (c-d) and slope (e-f) classes from 1985 to 2019; Land use and land cover map for the year 1985 and 2019 (g).

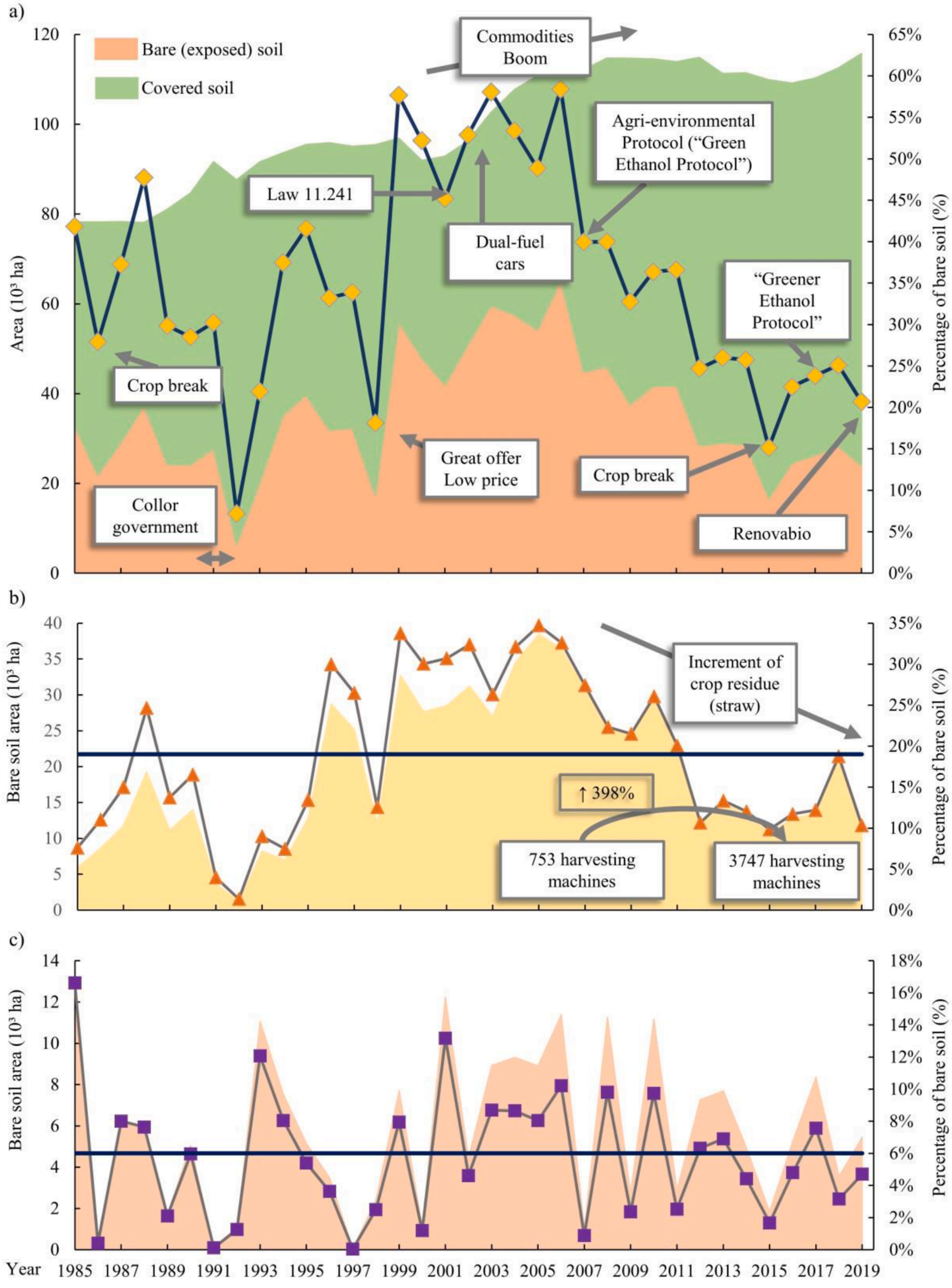

Fig. 3. Area of bare and covered soil (colored areas) and percentage of bare soil (line with points) in sugarcane area (a); area and percentage of bare soil in sugarcane areas in the dry season (b); and in the rainy season (c).

trend and can be performed on normally or not normally distributed data, which makes it a robust test.

The MK test started by applying an indicator function (sgn) on the difference between all possible pairs of measurements (Eq. (1)). The value measured in time j (xj) was subtracted from the values previously observed (xi), considering that time j > i. Then, these differences were used to define Kendall's statistics S (Eq. (2)):

$$sgn(\theta) = \begin{cases} +1 & for(\theta) < 0 \\ 0 & for(\theta) = 0 \\ -1 & for(\theta) > 0 \end{cases} \quad (1)$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(xj - xi) \quad (2)$$

where n is the length of the dataset. Based on S, the variance V (S) (Eq. (3)) and the normalized test statistics Z (Eq. (4)) were calculated:

$$V(S) = \frac{1}{18}[n(n-1)(2n+5)] \tag{3}$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{V(S)}} & if S > 0 \\ 0 & if S = 0 \\ \frac{S+1}{\sqrt{V(S)}} & if S < 0 \end{cases} \tag{4}$$

where the null hypothesis of no trend was rejected, if the absolute value of Z was higher than the theoretical value of Z(1-α/2) (at 0.05 level of significance). A positive S value indicated an increasing trend while a negative S indicates a decreasing trend. The magnitude of the trend was represented by the Sen's slope (Sen, 1968) calculated over the time period. To perform the MK test the rkt package in R software was used (Marchetto, 2021).

3. Results and discussion

3.1. Expansion of sugarcane land use

The cultivation of sugarcane in the studied region has expanded over the years, from a planted area of 78 thousand ha in 1985 to almost 116 thousand ha in 2019 (an increase of 48% - Fig. 2a), lower than Brazil increase since the 1980s (150%) (Cherubin et al., 2021b). The most part of this expansion occurred in São Paulo State (Franco et al., 2015; Cherubin et al., 2021b). Meanwhile the pasture dimension was reduced, from 75 to 38 thousand ha in the same period. Today, the areas classified as agriculture and pasture remained without major changes. Results are in agreement with other regions evaluation (Loarie et al., 2011; Hernandes et al., 2021; Cherubin et al., 2021b). Adami et al. (2012) appointed the expansion of sugarcane, in center-southern Brazil, occurred 70% over degraded pasture lands. Jaiswal et al. (2017), Spera et al. (2017), and Oliveira et al. (2019) consider that the most sustainable way for Brazil to expand sugarcane areas would be to occupy areas of degraded pastures. Different authors point out that the culture tends to expand in areas close to the mills, to reduce harvesting and logistic costs, even if this implies expanding a wide range of soil and slope conditions (Caldarelli and Gilio 2018; Hernandes et al., 2021; da Rocha and Sparovek et al., 2021).

The increase in sugarcane areas occurred mainly in the sandy and medium sandy soils types, with the expansion of approximately 248.5 and 64.4%, respectively (Fig. 2b). In the loam-clayey, the increase was only 9.1% and in the clayey one, there was a reduction of 4.6% (Fig. 2b). Catelan et al. (2022) correlated crop productivity with soil magnetic susceptibility, which is closely linked to the amount and type of clay. Regarding soil types (classification), sugarcane advanced significantly in the Lixisols/Acrisols, Leptosols, and Arenosols, with 92.9, 72.2, and 540.6%, respectively (Fig. 2c-d). In the Ferralsols, there was an increase of only 2.5% and in Nitisols we see a reduction of 11.9% (Fig. 2c-d). These expansions are in agreement with Donagemma et al. (2016), for whom the main central Brazilian area is expanding under sandy soils. These soils are extremely fragile and need special necessities such as soil conservation, different management, fertilizers and carbon care, cover crops, to consolidate its use in this expansion frontier of agriculture, and maintain its health (Carneiro et al., 2020). Despite this, other soils are under threat such as because results indicate the expansion of sugarcane to areas of greater susceptibility to water erosion (98.4% Strong rolling). Indeed, these areas have presence of textural gradients (Lixisols/Acrisols), shallow (Leptosols, Fig. 2d), lower clay contents (Arenosols), and higher slopes (Sparovek and Schnug, 2001). The result of the expansion in these types of soils are impacts on less soil water infiltration, low soil water storage volume, low aggregation, and higher surface runoff speed and strength, respectively. Lixisols/Acrisols to erosion (Fig. 2c) (Corrêa et al., 2019). Oliveira-Andreoli et al. (2021) consider sugarcane areas associated with sandy soils and high declivity to be of high fragility. Silva et al. (2021) evaluating the production of sediments in a watershed, showed that areas with sugarcane cultivation in undulating terrain, were the ones that generated the greatest amount of sediments. Therefore, conservation agriculture practices and the renewal of sugarcane plantations must be prioritized in these areas at the ideal time for each type of soil class.

3.2. Historical moments and bare soil area

Fig. 3a shows a temporal alteration on sugarcane management, for which needs an historical explanation. The sugarcane production systems (Vitti and Prado, 2012) have undergone adaptations over the years, mainly motivated by the advance of mechanized harvesting in the sugarcane fields (Aguiar et al., 2011; Demattê and Demattê, 2009). This initiative began in 1996, and intensified after the creation of state law 11.241 in 2002, that established a deadline for the end of pre-harvest burning, and mainly due to the Agro-environmental Protocol ("Green Ethanol Protocol") for the sugar-energy sector signed in 2007, which essentially provided the anticipation of this deadline (Aguiar et al., 2011).

This intensification is proven in the comparison of burning and non-burning area studies in the state of São Paulo (de Aguiar et al., 2009; Rudorff et al., 2010). Authors presented in the 2006/2007 33.5% of the area harvested without the use of fire and in the 2008/2009 increased to 49.1%. Valente and Laurin (2021) highlight the effectiveness that the protocol had in reducing fires. Although it was not the main objective, the effectiveness of the Green Ethanol Protocol brought as another benefit, the maintenance of soil covers through the residue left after harvest (straw). Today, harvest 2020/2021 authorizations for burning were only 0.20% of the total sugarcane area in the state of São Paulo (Secretary of Infrastructure and Environment, 2021). Also, according to UNICA (2021), there was an increase of 398% in the number of harvesting machines in the state of São Paulo from 2007/2008 to 2016/2017. Recently, other public policies have been gaining prominence and may contribute to the improvement of soil conservation management in the crop, such as the "Greener Ethanol Protocol" (Secretary of Infrastructure and Environment, 2021) and the Renovabio (Klein et al., 2019; Carvalho et al., 2021; Grangeia et al., 2022).

These historical facts and public policies explains the increase of raw sugarcane that allows the presence of straw covering the ground (Fig. 3a). After 2006 a process of reducing areas with bare soil began, leaving an annual average of 53% in the period 1999–2006 to an average of 23% in the period 2012–2019. This information is also perceived when analyzing the dry season that is inserted in the harvest period (Fig. 3b), whereas in the rainy season this tendency does not exist (Fig. 3c), as part of the culture practices. In the off harvest season (rainy period) the area of bare soil is a consequence of the renovation (replanting) of the culture (renovation is about each 5 years), or areas that suffered pre-harvest burning and crop regrowth was not enough to cover the soil. Thus, in the past, despite the soil not being prepared, it was exposed between harvesting and regrowth, so the GEOS3 method (SYSI creation) detected these areas.

The increment of crop residue (Fig. 3b) brought benefits for soil conservation and quality. According to Bezerra and Cantalice (2006) and Valim et al. (2016), straw promotes a reduction in the impact of raindrops and surface runoff, thus resulting in less disaggregation of soil particles and reduction of erosion processes. Martins Filho et al. (2009) found that the water infiltration rate in a Red-Yellow Lixisol is higher in areas with 50 and 100% coverage by sugarcane plant residues than in areas with its absence. A reduction in the maximum temperature of the soil is also observed (Santos et al., 2022; Corrêa et al., 2019), and larger soil moisture conservation (Gmach et al., 2019). In addition, over the

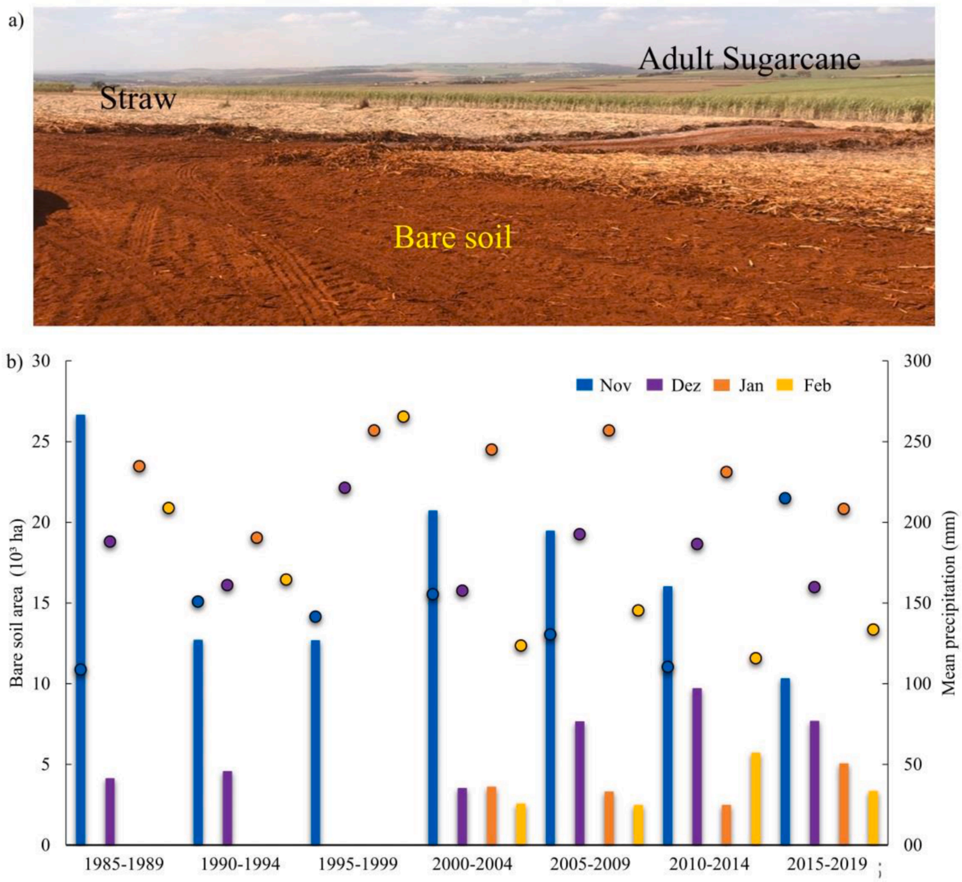

Fig. 4. Illustration of three situations, bare soil, straw after harvesting and adult sugar cane (a). The bare soil area (bar) during the rainy season over the years every 5 years, and historical average precipitation (point) (b).

cycles, the increase in soil organic carbon (SOC), and CEC contents occurs, thus improving the chemical quality of the soil (Correia and Alleoni, 2011; Signor et al., 2016, 2014).

In addition to the changes presented as a result of the advance of mechanization in sugarcane fields, the annual variation in the area and percentage of bare soil is affected by climatic and economic moments that occurred during the period (Fig. 3). In years of low rainfall, as occurred in the region in 1985 and 2014, the low area of soil discovered in the following year is notorious due to the crop failure. Low production leads to a reduction in the income of the producer, who, without capital, reduces the areas of renewal (replanting). (Fig. 3a). The fall of bare soil in 1986 is also motivated by the severe economic crisis that Brazil was going through and the drop in oil prices, which led the government to reduce incentives for ethanol production (Stolf and de Oliveira, 2020; UNICA, 2021).

During the Collor government (1990–1992), Brazil was going through a serious economic crisis (Fig. 3a). Thus, in the sugarcane sector, there was a reduction in incentives, high production cost, and a process of deregulation, which began with the extinction of the IAA (Institute of Sugar and Alcohol). The IAA was responsible for the quota system, which defined how much each mill could produce during the harvest, so the IAA planned and monitored all that production (Bray et al., 2000). Thus, with the extinction of the institute, the quota system was abolished, thus generating a period of instability in the sector until they managed to coordinate on their own (Stolf and de Oliveira, 2020). So, all these factors motivated the reduction of bare soils in this period.

In Fig. 3a, it is possible to observe the moments of bare soil increase, as occurred in the years 1999 to 2006. This was motivated by the high perspective that the sector was going through with the increase in the prices of agricultural commodities worldwide. This was also impacted by the insertion of commercial dual-fuel cars (ethanol and gas, the called 'flex) in 2003 (Caldarelli and Gillio, 2018). Schlindwein et al. (2021) point out that the main cause of sugarcane expansion in Brazil is due to the successful adoption of flex-fuel vehicles. Thus, new areas were transformed for the cultivation of sugarcane, and the renovation areas were greater, since the producers wanted to guarantee higher yields as a result of the good prices at the time. The early 2000s are known in the agricultural sector as the "Commodities Boom". Between 2007 and 2008 occurred a rapid internationalization of the sector, which also contributed to the expansion (Caldarelli and Gilio, 2018). The 2009 economic crisis that brought stagnation and soon after (Caldarelli and Gilio, 2018), in 2012, the government interference in gas prices, which impacted on alcohol and broke more than 100 mills. In 2018, this policy changed again and ethanol started new increasing era. Therefore, it is possible to verify that economic factors, laws and public policies have a direct impact on sugarcane production, corroborating with Catañeda-Ayarza and Godoi (2021), which ends up interfering more or less sharply with soil safety in sugarcane-producing areas.

3.3. Distribution of bare soils in months of risk

The three situation of surface (bare soil, straw after harvesting and adult sugar cane) are illustrated in Fig. 4a. The rainy season in São Paulo State concentrates 60% of the intra-annual erosivity, with the highest mean monthly values observed in January (Teixeira et al., 2021). It is possible to verify a change over time in the distribution of areas with bare soil during the rainy season (Fig. 4b). For the month of November there is a reduction in the area over time. Although, November

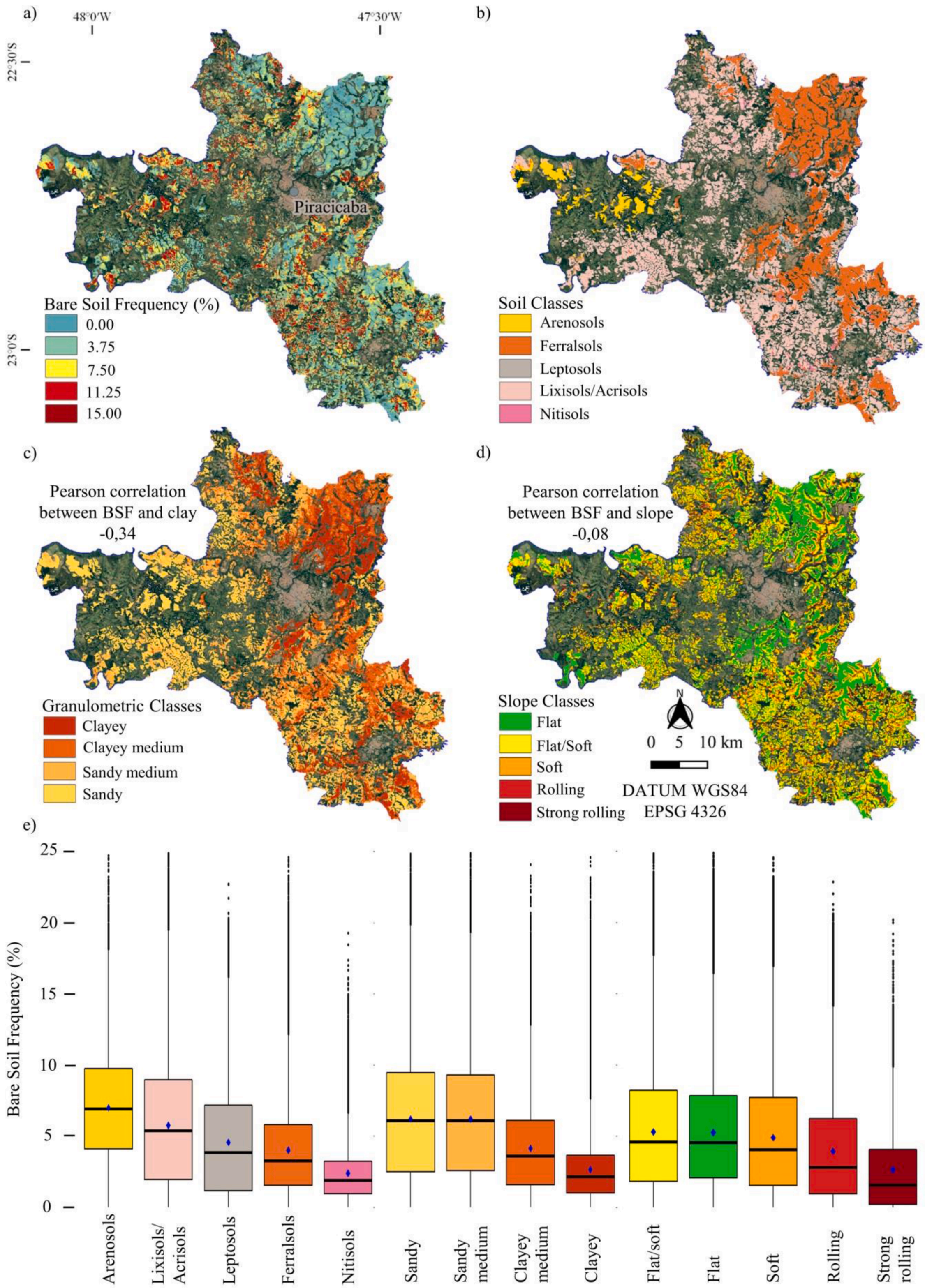

Fig. 5. Bare soil frequency map from 1985 to 2019 for sugarcane areas (a); Soil (b), Granulometric classes (c) and Slope classes (d) maps for sugarcane areas; Boxplot of bare soil frequency for maps classes (e).

continues to be the month, of the rainy season, with the highest area of bare soil. This can be explained for two reasons, due to the increase in mechanized harvesting along the time, which led to a decrease in bare soil areas due to pre-harvest fire in October and November, or a change in the management of crop planting in the region, leaving a system from "12 months-cane" planting to "18 months-cane". This second point can be reinforced by the increase, along the time, of bare soil areas in December, January and February. The planting season is considered the most impacting for soil conservation in the sugarcane crop (Machado et al., 2021). Li et al. (2021) demonstrated that erosion and nutrient losses were 2–3-fold higher in plant cane than in rattons Teixeira et al. (2021). reinforced the importance of information on rainfall erosivity and erosivity density in soil conservation planning for sugarcane activity in the State of São Paulo.

The progress of renovation (replanting) areas, especially in December and January, which present intense rainfall and a greater volume of precipitation, requires the correct planning that will be reformed due to the high propensity to erosion (De Maria et al., 2016). It is recommended that only flat, clayey, fertile, and high CAD areas be replanted in these months (De Maria et al., 2016). Traditionally, in the renovation of a sugarcane area, the first step is to turn the soil over, (plowing, subsoiling and harrowing) due to physical, chemical, or biological problems (conventional tillage), which promotes the breakdown of soil particles and soil organic carbon oxidation (Cerri et al., 2011; Bolonhezi et al., 2019; da Luz et al., 2020). But the presence of bare soil in the rainy season could increase soil lost by erosion (Corrêa et al., 2019). Then, minimum, no-tillage or localized tillage (preparing the soil only in the planting line, promoting greater maintenance of the straw) and use of cover crops should be considered (Carneiro et al., 2020). According to studies by Prove et al. (1995), the average soil loss for conventional tillage systems was 148 t ha^{-1} $year^{-1}$, whereas in the no-tillage system it was less than 15 t ha^{-1} $year^{-1}$. Also, according to studies in the Ferralsols during 44 days, the conventional tillage releases 954.79 kg ha^{-1} of carbon to the atmosphere, while that reduced tillage and minimum tillage releases 141 and 15.2 kg ha^{-1}, respectively (Silva-Olaya et al., 2013). However, some authors report that the sector still resists the adoption of more conservationist soil preparation methodologies (Fuentes-Llanillo et al., 2021).

Different studies have pointed out the importance of soil conservation practices in the sugarcane crop, mainly due to the production of sediments and pollutant transport by runoff Amorim et al. (2021). studying the origin of sediments from a basin in northeastern Brazil, detected that the second largest source of sediments was the sugarcane crop Machado et al. (2021). studying the variation of runoff coefficient in a watershed in Piracicaba region, largely occupied with sugarcane, pointed out the impact of soil management on the runoff produced. da Anjinho et al. (2021) pointed to agriculture (sugarcane) and soil type were key factors to the erosion and sedimentation susceptibility. Furlan et al. (2021) evaluated the impact of sediments from sugarcane area on wetlands. In Australia, there is great concern about soil management practices in the sugarcane crop, mainly due to the potential impact of sediments and polluting compounds on the Great Barrier Reef (Vilas et al., 2022).

3.4. Soil types and bare soil frequency: vulnerability to degradation

We observed a high spatial variation in the frequency of bare soil in the period from 1985 to 2019 in sugarcane areas (Fig. 5a). In the northeast there is a lower bare soil frequency (lower exposure frequency) when compared to the northwest and southwest sites, which have higher frequencies related to the predominant soil types and clay contents (Fig. 5b-c). The distribution of BSF in relation to clay contents presented a negative correlation of −0.34, while, relating to slope, was −0.08, thus showing a greater dependence on the clay (Fig. 5c-d). Catelan et al. (2022) and Marques et al. (2014) pointed out a positive correlation between sugarcane yield and soil clay content. Productivity is the main factor considered in the need to replant sugarcane (Cheavegatti-Gianotto et al., 2011), then, the maintenance of productivity implies, as a consequence, less soil tillage over time. Therefore, any practice that contributes to the increase in the longevity of the sugarcane crop, will imply a greater number of ratoons and will reduce the need for replanting, when there is more disturbance of the soil, and consequently less environmental impact (Chagas et al., 2016). May be cited as practices that contribute to increased longevity: compaction control (Lima et al., 2022; Panziera et al., 2022), use of varieties in suitable production environments (Barbosa et al., 2021), adequate fertilization (Pancelli et al., 2022), harvest performed with adequate speed (Martins et al., 2022), irrigation (Walter et al., 2014), among others

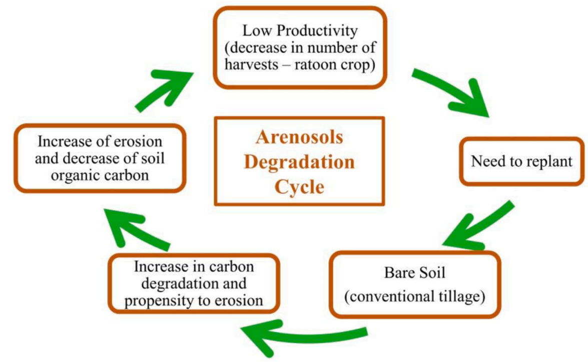

Fig. 6. The Arenosols Degradation Cycle as a consequence of management practices.

The Arenosols, present in the northwest region (Fig. 5b), are located in flat to soft undulating reliefs and present a high rate of water infiltration into the soil. However, these soils require attention because they are sandy texture and low levels of SOM, therefore, they have a low particle aggregation capacity, which gives them a high propensity to erosion, especially rill and gully erosion (Carneiro et al., 2020; Cunha et al., 2011; Santos, 2018; Thomaz and Fidalski, 2020). The low levels of SOM plays a fundamental role in its quality, such as low CEC, slow release of P, N, S nutrients, lower availability of micronutrients and water retention (Cunha et al., 2011). This soil type had the highest BSF mean, 7.02% (Fig. 5e), which is harmful to the maintenance or increase of SOM, since maintain the soil uncovered promotes SOM decomposition and other impacts (Cerri et al., 2011; Cherubin et al., 2021a; Morais et al., 2020; Popin et al., 2020) Sayão et al. (2020). demonstrated that bare sandy soils, from the same region of our study, had the highest surface temperature which contributes to an even greater SOM mineralization.

These observations are alarming since the management adopted for Arenosols, in the studied region, indicate a soil degradation cycle (Fig. 6). Breaking this cycle can be promoted through the adoption of management practices such as: greater input of organic and mineral fertilizers, as vinasse and filter cake, cover crops/green manure, intercropping (Shen et al., 2019; Singh et al., 2021), minimum or no-tillage (Martíni et al., 2021), practices that enable an increase in the number of ratoons (longevity) and maintenance of the straw. Cherubin et al. (2021a) concluded that sandy soils were more prone to soil health degradation, when straw is removed and the healthier soils were associated with higher sugarcane yields. Shukla et al. (2020) emphasize that maintaining soil organic carbon and increasing crop productivity is an inseparable issue, without addressing both issues simultaneously, the sustainability of production system could not be achieved.

In the northwest and southwest regions, Lixisols/Acrisols are the main soil classes (Fig. 5b), and present the second highest average of the BSF (5.78%). These soil types are susceptible to erosive processes, as they are located in more rugged reliefs and have increase of clay in-depth, resulting in a textural gradient, which makes it difficult for water to infiltrate, and increasing surface runoff (Fig. 2a), to finally transport the eroded sediment (Jarbas et al., n.d.; Santos et al., 2018; Zaroni and Santos, n.d.). According to Martins Filho et al. (2009) an Lixisol without vegetation cover, there is an enrichment ratio in the eroded sediment of 2.7 (SOM), 3.8 (P), 1.3 (K), 3.9 (Ca), and 2.9 (Mg) times when compared to soil 100% covered, i.e., resulting in a greater loss of SOM and nutrients when to bare.

Leptosols (Fig. 2d) located in 6.21% of the area (Fig. 5b) are soils with a low degree of pedogenetic development, and low depth due to the mandatory contact of the A horizon to the R/C/Cr horizons within 50 cm of the surface and are found in strong declivity reliefs. Such characteristics increase the propensity to erosion (Curcio et al., n.d.; Santos et al., 2018). The presence of lithic contact prevents water infiltration into the

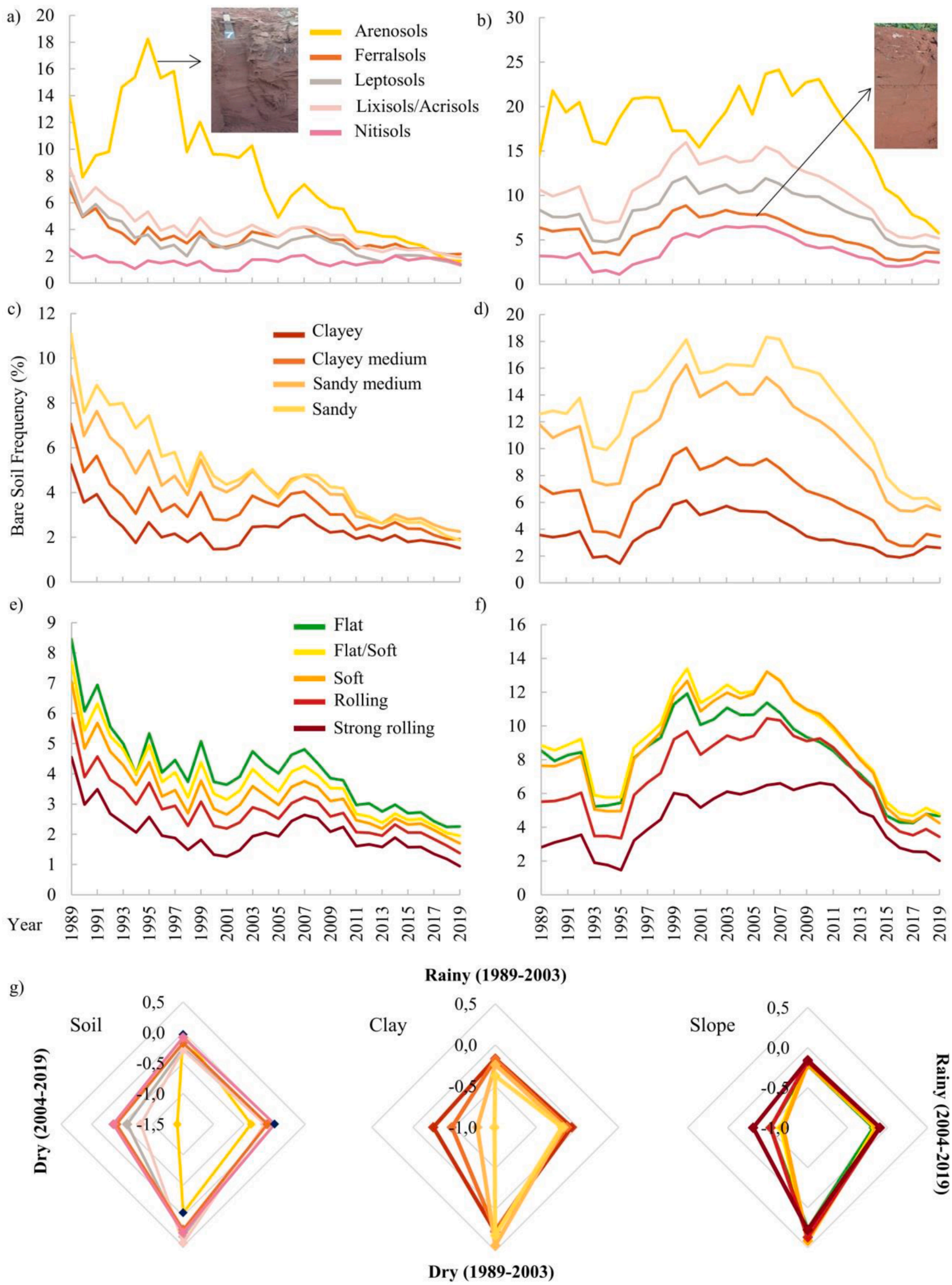

Fig. 7. Mean bare soil frequency in rainy season (a-c-e) and dry season (b-d-f); Magnitude of the trend by Sen's slope (g).

soil and results in a low storage volume, favoring surface runoff. This gains strength due to the high declivity, so its BSF mean of 4.58% in the period, (Fig. 5e) favors it is degradation (Weill and Sparovek, 2008).

Finally, the Ferralsols and Nitisols had the lowest BSF averages, 4.02 and 2.42%, respectively (Fig. 5e). Ferralsols are deep, well-drained, with strong profile percolation and low fertility. Clay contents range from 150 to 800 g kg^{-1} and are mostly found in flat to soft undulating reliefs (Fig. 5b) (Santos, 2018; Sousa and Lobato, n.d.). Due to these characteristics, the propensity to degradation, such as nutrient deficiency and erosion, occurs mainly in sandy-medium Ferralsols, which have lower aggregation and lower SOM (Carneiro et al., 2020; Donagemma et al., 2016; Sousa and Lobato, n.d.). Thus, as with Arenosols, greater coverage of these soils is necessary to promote the maintenance and increase of SOM, as well as water retention to reduce nutrient leaching. In the northeast sector are found most of the Ferralsols (Fig. 5b) with higher clay contents (Fig. 5c) and lowest BSF (Fig. 5a). It is

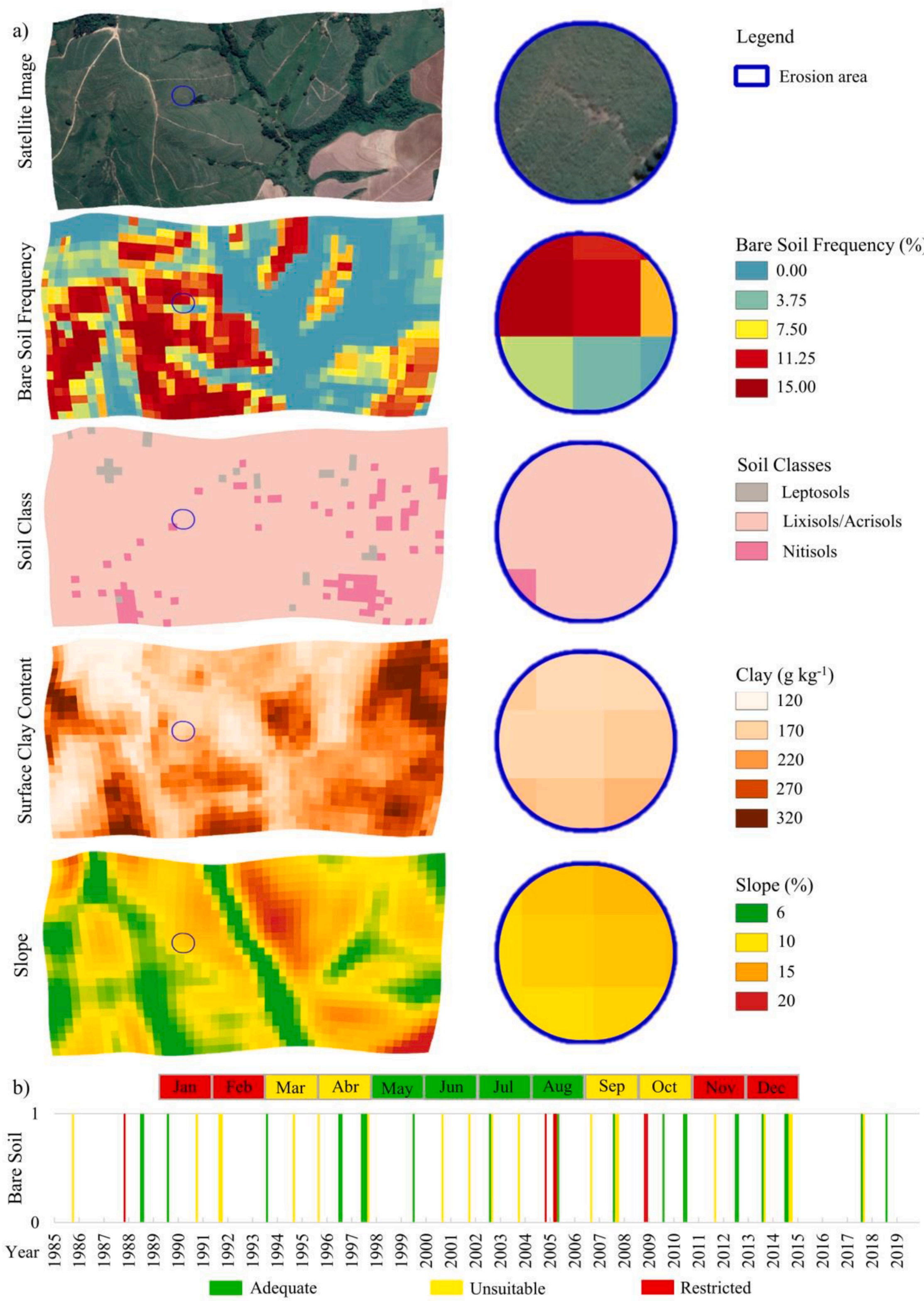

Fig. 8. Satellite Image, Bare Soil Frequency, Soil Unit Class, surface clay content and Slope map in an area with the presence of erosion (a); Moments of soil was bare per month from 1985 to 2019 (b).

in agreement with that was pointed out previously, that, there is a high correlation between clay contents, productivity and the need of replant.

On the other hand, Nitisols are also deep and well-drained soils with good structure, and clay contents (above 350 g kg^{-1}), without the presence of textural gradient, and are found in smooth wavy to strong wavy reliefs (Santos and Zaroni, n.d.; Santos, 2018). In areas with more sloping relief, there is greater susceptibility to erosion processes, so keep the soil uncovered in these regions must be associated with other conservation practices to ensure soil security (Santos and Zaroni et al., n.d.). Mechanized harvesting without previous burning provided the maintenance of cover in these soils, however brought problems with soil compaction, especially in clayey soils, harming its porosity and density (Braunack et al., 2006; Oliveira et al., 1995). Some authors point out that, in some cases, up to 60% of the area may be affected by compaction (Souza et al., 2014; Esteban et al., 2019). The physical impediment caused by the high traffic of machines impairs the infiltration of water into the soil, promoting a greater volume of surface runoff, which can result in erosive processes (Ceddia et al., 1999; Fiorio et al., 2000; Prado and Centurion, 2001). This surface runoff with the presence of sediments is harmful also to aquatic systems, as the deposition of these sediments in rivers, lakes or reservoirs impacts water quality and ecosystem biodiversity (Politano and Pissarra, 2005). In addition, compacted soils present unfavorable conditions for the growth and development of the sugarcane root system (De Sousa et al., 2019), thus resulting in lower productivity (Arruda et al., 2021) that will contribute to the producer's decision-making for the anticipation of sugarcane replant, i.e., reducing longevity. Marin et al. (2019) appointment that the negative effects of mechanical harvest on soil structure is one aspect related to yield decline in commercial sugarcane areas. Another negative aspect is that conventional soil preparation is often seen as the main way to reduce compaction, although different studies have shown its low effectiveness, especially after the first harvest (Guimarães Júnnyor et al., 2019; Martíni et al., 2021). Some compaction mitigation practices are: the adoption of controlled traffic (De Sousa et al., 2019; Barbosa et al., 2021), spacing and machine gage adjustment (Chabrillat et al., 2019; Rossi Neto et al., 2018)

3.5. Monitoring the bare soil frequency

Monitoring the average frequency of bare soil in two different seasons, rainy (Fig. 7a,c,e) and dry (Fig. 7b,d,f), showed a downward trend in the two periods, i.e., the BSF average has declined over the years (Fig. 7g). In the dry season, only in the second period there was a downward trend, and in the first, there was an upward (Fig. 7g). The Arenosols did not trend in the first periods of the dry and rainy season and the Nitisols either did not in the second period of the rainy season.

The tendency to reduce the frequency of bare soil in the rainy season is of great importance for their conservation and soil security. This reduction shows the better planning and understanding of the sector in which lands can be bare at certain times of the year. This could be related to the advancement of the concept of "Production Environments", that considers the interaction between soil, climate, and plant (Barbosa et al., 2021; Catelan et al., 2022; Demattê and Demattê, 2009), use of cover crops (Carneiro et al., 2020); migration from 12 months-cane planting, to 18 months-cane, adoption of MEIOSI (Portuguese acronym for Methods Inter-rotational Occurring Simultaneously) planting system when it is possible (Oliveira et al., 2018). According to Landell et al. (2003), for adequate knowledge of the production environment in sugarcane culture, it is necessary, first, to classify the given soil. Besides, Donzelli et al. (2018) emphasizes the importance of an adequate soil mapping for production environments classification and soil groups for agricultural management.

In particular, the Lixisols/Acrisols and Leptosols (Fig. 2c,d), that presents a high propensity to degradation when bare (Corrêa et al., 2019; De Maria et al., 2016), presented a downward trend of 0.28 and 0.25% rainy season^{-1} year^{-1} in the first period and 0.16 and 0.14% rainy season^{-1} year^{-1} in the second period, respectively (Table A1). The Arenosols (Fig. 7a), indicated a significant downward trend of 0.38% in the second rainy season^{-1} year^{-1} (Table A1). However, it is the soil class with the highest BSF for all period. Ferralsols presented low variation (Fig. 7a,b). To keep the soils uncovered promotes an increase in temperature, which leads to the acceleration of SOM decomposition (Silva-Olaya et al., 2013), and consequently, affecting soil biota (Demattê et al., 2020). Therefore, the upward trend presented in the first period, motivated by the increase of newly cultivated areas, was detrimental to soil conservation. However, the downward trend in the second period, caused mainly by the advance of mechanized harvesting, shows the improvement in the biological and chemical conditions that the sector has been providing to its soils. In particular, soils of the sandy and sandy medium clay classes showed a downward trend of 0.99 and 0.78 dry season^{-1} year^{-1}, respectively (Table A1). In general, such classes do not have high levels of SOM, therefore, promoting their maintenance or increase is of paramount importance for soil quality, providing greater particle aggregation, increasing CEC and nutrient release and increasing water retention.

3.6. Site-specific monitoring in an eroded area

We made a site-specific evaluation regarding the erosion identification (Fig. 8a). The site had a surface with clay content of 170 g kg^{-1}, a slope of 11.5%, and classified as Lixisols/Acrisols. This information infers that it is an area of great erosion susceptibility, which is seen in the satellite image. The observed erosive furrow proves that the soil management was not adequate in this area and the control practices, such as the presence of contour lines and terracing (Fig. 8a), were not sufficient or poorly dimensioned.

Also, this region had high BSF in the period from 1985 to 2019 (Fig. 8b). We observed that until 2014, in almost every year, at the same site-specific the soil was bare, except for the years 1986, 1992, and 1998. It was caused by the sugarcane pre-harvest burning that occurred in the past or by the conventional tillage during the period of sugarcane replanting. Thus, analyzing from 1985 to 2014, 9% of exposures (soil was bare) occurred in months considered restricted, 44% in unsuitable and 47% in adequate periods. The exposure in restricted and unsuitable months may have favored the erosive process. On the other hand, after 2015 (despite the short period of analysis), it is observed that the number of years without bare soil presence increases, which could be explained by the introduction of mechanized harvesting. In any case, and for this region, planting and harvesting should be prioritized between May and August, which are considered suitable for the exhibition in agreement with De Maria et al. (2016). In this simple site-specific evaluation, it is possible to observe that BSF is a good tool to identify areas with a high propensity to soil degradation, promoting information for soil security through its efficacy such as a technique for soil monitoring.

3.7. Limitations and advantages

Some points can be pointed out as the main limitations related to the creation of images of bare soil and bare soil frequency. The definition of threshold values for the indices used to mask unexposed (soil covered) pixels varies with the region and scale (Demattê et al., 2020; Gasmi et al., 2021; Silvero et al., 2021a). Zepp et al. (2021) pointed out as not robust enough the threshold values previously pointed out by Rogge et al. (2018). The high presence of clouds and shadows in a certain region and/or the season are another limitation (Silvero et al., 2021b; Mzid et al., 2021). Silvero et al. (2021a) obtained percentage of bare soil pixels lower than 15% in the moist season in a tropical area and concludes that twenty images from the dry period would provide barer soil pixels than twenty images from the moist season. Another issue is the satellités temporal resolution, the shorter the revisit time, more images can be obtained and, consequently, barer soil pixels (Silvero et al., 2021a; Silvero et al., 2021b; Mzid et al., 2021).

Despite these limitations, the use of multi-temporal images for environmental monitoring has been consolidated and pointed out as having a high potential for use (Canata et al., 2021; Som-ard et al., 2021; Zepp et al., 2021). As mentioned before, several works have shown solid results (Silvero et al., 2021b). Furthermore, the free open access of satellite images, like Landsat and Sentinel missions, especially in cloud-based platform such as the GEE, is a great opportunity (Aguiar et al., 2011; Silvero et al., 2021a) and facilitates the study of large areas (Chikhaoui et al., 2005). A future possibility is the fusion of

Table A.1
Results of the trend analysis of the average bare soil frequency.

Class	Rainy season 1989–2003			2004–2019			Dry season 1989–2003			2004–2019		
	Tau	Slope	p-value	Tau	Slope	p-value	Tau	Slope	p-value	Tau	Slope	p-value
Arenosols	−0.09	−0.03	0.692	−0.88	−0.38	<0.001	−0.03	−0.05	0.921	−0.77	−1.40	<0.001
Ferralsols	−0.56	−0.17	0.004	−0.75	−0.12	<0.001	0.45	0.23	0.023	−0.87	−0.41	<0.001
Leptosols	−0.60	−0.25	0.002	−0.65	−0.14	<0.001	0.54	0.34	0.006	−0.88	−0.59	<0.001
Lixisol/Acrisols	−0.64	−0.28	<0.001	−0.77	−0.16	<0.001	0.54	0.45	0.006	−0.88	−0.81	<0.001
Nitisols	−0.49	−0.08	0.013	0.02	0.00	0.96	0.45	0.28	0.023	−0.82	−0.36	<0.001
Clayey	−0.58	−0.17	0.003	−0.77	−0.07	<0.001	0.49	0.27	0.013	−0.82	−0.25	<0.001
Clayey medium	−0.60	−0.18	0.002	−0.77	−0.13	<0.001	0.43	0.26	0.029	−0.87	−0.47	<0.001
Sandy medium	−0.62	−0.24	<0.001	−0.73	−0.17	<0.001	0.47	0.44	0.018	−0.85	−0.78	<0.001
Sandy	−0.68	−0.37	<0.001	−0.77	−0.19	<0.001	0.62	0.31	0.002	−0.92	−0.99	<0.001
Flat	−0.60	−0.21	0.002	−0.80	−0.17	<0.001	0.54	0.28	0.006	−0.83	−0.53	<0.001
Flat/Soft	−0.62	−0.21	<0.001	−0.75	−0.15	<0.001	0.56	0.42	0.004	−0.87	−0.66	<0.001
Soft	−0.66	−0.20	<0.001	−0.73	−0.13	<0.001	0.60	0.41	0.002	−0.88	−0.69	<0.001
Rolling	−0.70	−0.17	<0.001	−0.70	−0.10	<0.001	0.60	0.37	0.002	−0.82	−0.54	<0.001
Strong rolling	−0.77	−0.16	<0.001	−0.68	−0.10	<0.001	0.58	0.28	0.003	−0.63	−0.32	<0.001

multi-temporal images from different sensors that would allow a greater number of images with a shorter revisiting time for an area (Silvero et al., 2021a). Finally, specifically regarding soil security, Zepp et al. (2021) conclude that the use of multi-temporal composite images contributes with the information about where and when soils are bare, that is a valuable information for soil erosion studies.

4. Conclusions

We confirm our hypothesis that the use of multi-temporal satellite images makes it possible to evaluate aspects of soil management and their changes in sugarcane areas, and to relate them to soil security, especially those linked to erosion. The use of SYSIs showed that the bare soils areas under sugarcane cultivation reduced after the "Agro-environmental protocol". However, we confirmed that the expansion occurred over soils more prone to erosion (Lixisols/Acrisols, Arenosols and Leptosols with sandy and sandy medium surface texture). Despite the challenges imposed by mechanized harvesting in relation to the physical properties of the soil, their cover maintenance contributes to its conservation, safety, and quality, that is, a necessary change for the development of more sustainable agriculture. Among the historical period of 35 years, the ups and down on soil tillage and bare soil area in the sugarcane culture, had several factors such as climate, commodities price, public policies, governments decisions and the learning curve of farmers.

The use of the BSF allowed verifying the reduction of the bare soil frequency in the rainy season, in particular, into the Lixisols/Acrisols, Leptosols, and Arenosols soils types. This confirms the best knowledge of the sector in relation to the best period to tillage each soil class. However, it is necessary to continue the downward trend in order to reduce the propensity to degradation, especially in Arenosols and soils with a sandy surface texture, that are soils with highest BSF in all period. In the dry season, the reduction in the average BSF in the second period confirms the importance of the aforementioned protocol for soils.

It was not possible to verify changes in the area of bare soil during the rainy season (November to February) over the years. However, there was a decrease in bare soil areas during November and an increase during the December, January and February.

Finally, the site specific temporal analysis of bare soil in a given area, confirms the importance of remote sensing in environmental monitoring. The technique, proposed by Demattê et al. (2020) has important contributions in land inspection and the adoption of public policies on sustainability and soil conservation as impacts in soil security as well. Furthermore, this approach could be applied in other regions with sugarcane crop (i.e. Brazilian Northeast, Australia) either for past analysis or for future land monitoring.

Appendices

Supporting information

Fig. S1 – Main nomenclatures/terms used in the sugarcane crop cycle in the south-central region of Brazil (a). Harvest season and historical mean precipitation (mm), blue rainy months, yellow intermediate, orange dry months (b)

Table S1 – Definition of the main by-products of sugarcane used as fertilizers

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.soisec.2022.100057.

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