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Review

The soil conservation agenda of Brazil: A review of "edge-to-edge" science contributions

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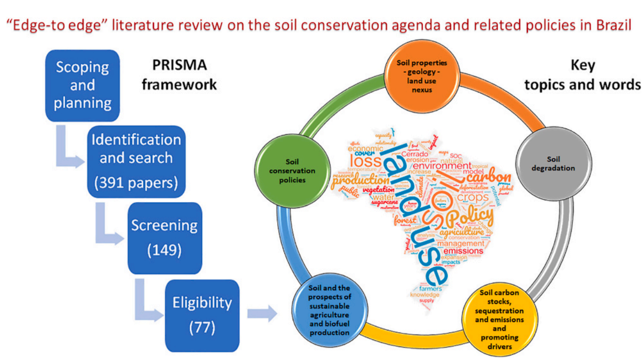
H I G H L I G H T S

- A PRISMA-based review on the Brazilian soil conservation agenda is presented.
- The review tackles socio-economic, policy and management topics of soil conservation.
- Key management topics comprise new technologies to mitigate soil degradation.
- Socio-economic standpoints comprise sustainable food and biofuel production.
- The review also highlights current discussions on soil carbon stocks, sequestration and emissions.

G R A P H I C A L   A B S T R A C T



A R T I C L E   I N F O

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A B S T R A C T

Soil conservation adheres to various United Nations Sustainable Development Goals while in Brazil is a constitutional obligation. To attain the goals and fulfil the obligation, laws, policies, governance and science must be imbricated to deliver suitable conservation solutions for the long term, namely appropriate to positively influence other downstream chains such as the food chain. However, in Brazil, a major world producer and exporter of food, weaknesses were recently diagnosed by judicial authorities concerning soil governance and coordinated land use policies. Integrated scientific assessments on soil conservation and mitigation of degraded soil are also lacking in this country. This was enough motivation and the purpose to present here a holistic view over the soil conservation agenda and promoting policies in Brazil, based on a literature review that followed the

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guidelines and criteria of PRISMA approach. We termed this analysis a review hinged on "edge-to-edge" science contributions for two reasons. Firstly, the intent of retrieving from the recently published literature solely papers centered on a relevant soil conservation topic (e.g., soil characterization, here called an "edge") but with complementary analyses over boundary topics (frontier "edges", such as soil degradation). Secondly, the intent of underlining the urgency to assist decision-makers with scientific evidence in all dimensions of the soil conservation agenda ("edge-to-edge" science), namely soil characterization (e.g., quality reference values), soil degradation assessment (e.g., anthropogenic-related soil erosion or contamination), soil degradation consequences focused on the carbon cycle (e.g., net CO_2 emissions and climate warming), sustainable management practices and production systems (e.g., no-tillage agriculture and integrated crop-livestock-forestry systems), and scientific evaluation of existing laws as well as of governance and policy programs with potential implications on soil quality (e.g., the Forest Code). Thus, this literature review addressed all these topics following a multidisciplinary discourse, which produced an extensive but comprehensive document about soil conservation in Brazil.

1. Introduction

Soil is the shelter of many living organisms and a primordial layer to store water and produce food. It is therefore a priority for conservation and justifies a whole agenda around the topic. Brazil is among the largest food producers on Earth. According to the EMBRAPA (https://www.embrapa.br/),theBrazilian company for agriculture and livestock research, in 2021 Brazil was the largest world exporter of soy (91 Mton) and the third largest producer of corn and beans (105 and 2.9 Mton, respectively), while 1/3 of sugar and the largest volume beef consumed on the planet have originated from this country. To protect the soil and ensure food security in the long-term, Brazil has built a robust legal framework, namely the Federal law no. 6.938, dated of August 31, 1981, which defines the soil as environmental resource, while the environment and all of its resources are inherently defended against damage by the Brazilian constitution (article no. 225). On the other hand, Brazil is probably the sole country on Earth with a Public Ministry entirely dedicated to environmental problems and assisted by a Military Police. Notwithstanding this status, some weaknesses were diagnosed by the Brazilian judicial authorities concerning soil governance and coordinated land use policies. In that regard, in the judgment no. 1942/2015, case no. 11.713/2015-1, the Court of Auditors from the Union (TCU) stated that "…*there is no comprehensive and delimited public policy for the management of soil resources*…". Besides, the TUC identified "…*lack of strategic planning by the federal government for the coordination of the various government actions related to the occupation and use of the territory and the promotion of soil and water sustainability. There are only diffuse government initiatives that, as a whole, have no logical chain to regulate the proper use of the soil. There is also no articulation between public institutions in forums for the implementation of initiatives related to the theme*…".

The weaknesses reported by the TCU in Brazil can also be identified in the published science worldwide. This is because many publications dedicate efforts to specific features of soil science, but panoramic views are lacking, where soil characterization, soil degradation, soil degradation consequences, management initiatives to preserve or restore a healthy soil condition, and policy frames for sustainable soil use, could be chained and discussed from a common multidisciplinary rationale. Indeed, we can refer abundant and interesting research on soil characterization for a diversity of purposes and using a multiplicity of techniques (Alkharusi et al., 2024; de Mello et al., 2023; Kazemnia Kakhki et al., 2024; Kruger et al., 2023; Siddiqua et al., 2024; Smestad et al., 2023); on soil erosion, soil contamination or soil degradation, including the controlling mechanisms (Ali and Muhammad, 2023; Asempah et al., 2024; Diallo et al., 2024; Dong et al., 2023; Li and Shi, 2024; Mendieta-Mendoza et al., 2023; Perović et al., 2023; Saha et al., 2024; Tomczyk et al., 2023; Wang et al., 2023; Xiong et al., 2023; Zhang et al., 2024); on soil degradation consequences such as net CO_2 emissions (Abdalla et al., 2018; Fernández-Ortega et al., 2024; Figueiredo et al., 2015; Mchunu and Chaplot, 2012; Odorizzi de Campos et al., 2022; Teodoro et al., 2024); on soil management practices to keep or improve soil quality (Bonetti et al., 2023; Dessie et al., 2023; Omer et al., 2023; Schreiner-McGraw et al., 2024; Zhao et al., 2023); or on soil policies (Grinlinton, 2023; Mulenga, 2023; Sánchez-García et al., 2023). However, this literature is frequently narrow-scoped because it sheds light over specific areas of soil research leaving the others on the shadow. In fact, soil research is so vast and reaches so many frontiers that studies addressing its full dimensionality might be a utopia. Nevertheless, there are studies working at the border of two or more dimensions with interest to the soil conservation agenda. In Brazil, we can refer a group of studies related with degraded pastures (da Silva Quinaia et al., 2021; Valera et al., 2017, 2016; Valle Júnior et al., 2019), which is a hot topic because the country is occupied with nearly 100 Mha of pastures that show some level of degradation and are away from the food production system, besides contributing to enhanced greenhouse gas emissions (Odorizzi de Campos et al., 2022). That group of studies is worth referencing because it combined soil characterization, soil degradation assessments and law/policy framing in a common discourse about pasture degradation, which taken together helped the Public Ministry of Minas Gerais to develop a software called SIPADE (http://sipade.com.br/assets/static/home/index.html). This software is to be operated by military police officers, being capable to confirm degraded pastures in the field and trigger the consequent legal regularization. This is a landmark of pasture restoration in Brazil, in parallel with the recent Presidential Decree no. 11,815, dated of December 5, 2023, which is the National Plan for the conversion of degraded pastures into sustainable agricultural and forestry production systems. In spite of being a good example of multidisciplinary force for soil protection, the aforementioned studies left outside the analysis various topics, such as pasture-related management practices or greenhouse gas emissions. The lack of comprehensive assessments on the Brazilian soil conservation agenda and promoting policies led us filling the gap through a review of literature. Reviews are, by definition, selections of papers based on specific criteria. In this case, a primary criterion was that selected papers had to be focused on more than one topic (e.g., soil characterization plus policy), as were those about the degraded pastures. We called these papers "edge-to-edge" science contributions, because they are thought to describe a topic (an "edge") in more detail while throwing links towards marginal topics (other "edges"). The advantage is that these links help chaining the entire selection to produce a coherent discourse across the review. Thus, the objective of this research was to deliver a review paper on soil conservation and related policies in Brazil, based on the aforementioned concept of "edge-to-edge" science. It is worth noting the review adherence to the total environment analysis. The pedosphere is on the spotlight because soil is the study object. However, the review results discussed in Section 4 revealed innumerous studies where other spheres play vital roles in the studies outcomes. For example, Section 4.1 revealed recent technological advances, such as digital soil mapping or visible–near infrared–shortwave infrared field reflectance spectroscopy, used to predict soil attributes or properties while including geology and topography in the assessments. This is a clear and important overlap between the pedosphere and the lithosphere. The section also exposed how the soil properties can determine aboveground biomass density and diversity in some climate-vegetation contexts, which highlights the overlap between the pedosphere and the biosphere. On the other hand, Section 4.2 presents an extensive evaluation of soil degradation mostly linked to human-related land use changes or contamination, revealing how the pedosphere directly intersects and is impacted by the anthroposphere. Finally, Section 4.3 is fully dedicated to the *nexus* land use or cover changes *versus* carbon dioxide changes, whereby studies evaluate, for instance, how expansion of cropland or lands used for biofuel production impact soil CO_2 emission, sequestration and stocks, underlining the strong connection between the pedosphere and the atmosphere dynamics. Taken altogether, the current review drives the reader through a comprehensive text about the Brazilian soil conservation agenda, making it evident how soil and its correct management is paramount to the total environment equilibrium.

2. Methodology

The literature review was based on Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher, 2009; Page et al., 2021), an approach used in many recent review studies (Duche Pérez et al., 2023; Kalinauskas et al., 2024; Ştefănică et al., 2021). Systematic reviews conducted this way comprise 6 steps: (1) scoping, (2) planning, (3) identification and search, (4) screening, (5) eligibility assessment, and (6) presentation and interpretation. For the review about soil conservation and promoting policies in Brazil, the focus of our research, the aim at the scoping and planning stages was to identify keywords capable of capturing scientific documents dealing with all dimensions of soil analysis, namely characterization of soil properties, degradation caused by erosion or chemical contamination, consequences of degradation such as net CO_2 emissions, management pathways to reverse degradation such as integrated crop-livestock-forestry production systems, and policies that create the environment to preserve a suitable soil condition. Put another way, the aim was to create a selection of "edge-to-edge" science contributions, where the "edges" are the aforementioned dimensions of soil analysis. At the end of steps 1 and 2, the selected keywords were "soil", "policy" and "Brazil", which moved to step 3 to be combined with Boolean operators and form a specific search query. The query was prepared in the SCOPUS database (https://www.scopus.com/). This is a worldwide repository comprising thousands of documents covering all sorts of scientific areas and hence suited for a survey of literature. Using searching tools embedded in this platform, the following code was used as search statement: TITLE-ABS ("soil" AND "policy" AND "Brazil"). This statement retrieved from the SCOPUS repository all documents that simultaneously contained, in the document's title or abstract, the three selected keywords. Stated this way, the selection would gather studies addressing unrestricted soil issues, such as physico-chemical characterization, degradation or management, but with mandatory reference to policy framing or implications, or studies about soil policies, all of them conducted in Brazil. The aim was to make a selection as much as possible composed of "multi edge" studies, meaning those addressing one edge (e.g., soil characterization) but looking at other edges as well (e.g., through providing subsides to policy), while excluding purely disciplinary studies (i.e., those addressing one edge disconnected from all the others). The statement used in step 3 retrieved 391 documents that moved to step 4 for screening. Now, the research statement was refined to TITLE-ABS("soil" AND "policy" AND "Brazil") AND PUBYEAR > 2009 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE,"ar")) AND (LIMIT-TO (LANGUAGE,"English")) AND (LIMIT-TO (EXACTKEYWORD,"-Brazil")). Thus, the screening step looked into the 391 documents and compiled the restricted sample of those published between 2010 and 2023 in English language, of type "article" (i.e., reviews, books, conference papers, etc. were excluded) and with "Brazil" (again) included in the keywords. The sample generated this way was composed of 149 articles that passed to step 5 where the eligibility criteria were applied. The conditions imposed to the 149 articles were that they addressed soil conservation in Brazil. Thus, articles describing soil conservation in Brazil but also in other countries were excluded. On the other hand, the studies should be about soil. Therefore, articles interested in soil but also in water or other spheres as well were excluded. Finally, the role of policy in the studies needed to be soil conservation. Consequently, articles addressing other political roles were excluded. In the end, the eligibility criteria led to a final selection of 77 articles, which were presented and interpreted in step 6 (see the Discussion section). The workflow of PRISMA method as applied to the present review is illustrated in Fig. 1.

3. Results

The 77 papers included in the review addressed topics and sub-topics of soil conservation and related policies, as listed in Table 1 (columns 2 and 3) and illustrated in Fig. 2. The word-cloud map of Fig. 3, prepared in the free online word cloud generator (https://www.wordclouds.com/),reveals the most common words used in the 77 article abstracts. The words "soil", "land use", "environment", "agriculture" and "policy" are dominant (> 100 words), working as threads across the selected studies. Other important words are "production", "crops", "loss", "emissions" and "forest" (≥ 50 words). As regards evolution in time, the number of papers increased from 11 in the 2010 – 2014 period to 31 in the 2015 – 2019 period and finally to 35 in the 2020 – 2023 period.

The number of articles per sub-topic is indicated in column 1 of Table 1 and the corresponding references in column 6. The first topic comprised studies that looked preferably at the soil from the characterization standpoint, including the relationship of soil properties with the geologic substratum or the impact of land uses, covers or changes on the soil properties. Then, the review shifted to studies more interested on remote sensed indicators of soil degradation (e.g., exposed soil), or to publications where some geology-soil property and some land use-soil property relationships were described as degradation. This latter group included studies that used the Universal Soil Loss Equation and sediment delivery equations to quantify soil erosion beyond tolerable thresholds or evaluate siltation of reservoirs caused by excessive soil losses. It also comprised cases of geogenic or anthropogenic soil contamination with metals or organic substances. The third topic talked preferably about soil carbon stocks and highlighted a specific consequence of soil degradation, which is net CO_2 emission and the consequent climate warming, while shedding light over reversing pathways (net sequestration). Having finished the carbon discussion, the review moved forward to the fourth topic, where the sustainable management of soil is considered pivotal to soil conservation or to the reversal of soil degradation, namely through implementation of crop-livestock-forestry production systems. Finally, in topic five the policy environment was evaluated as regards efficacy in improving soil condition, attracting adherents to more resilience production systems, or controlling the expansion of competing land uses. In all cases, the sub-topics addressed by the papers were the central "edge" but not the sole "edge", as imposed by the PRISMA criteria in this review. Besides topics and sub-topics, Table 1 indicates where the studies were conducted and the Brazilian biomes they stand for. Various studies spanned the entire country and all biomes while others were restricted to one or more states and biomes. Overall, the sample seems well representative of Brazil.

4. Discussion

The sequence of topic presentation used in Table 1, namely soil property characterization > geogenic or anthropogenic soil degradation > degradation-related CO_2 emissions and reversing pathways > sustainable soil management as key measure of soil degradation reversal > promoting land use policies as regulatory environment, was selected to clarify even further what we mean about "edge-to-edge" science and how the concept was applied to the Brazilian's soil conservation agenda in this study. As the reader will understand, the scientific studies reviewed and discussed in the forthcoming sub-sections reveal how science can support all phases of decision-making (the "edges"), from

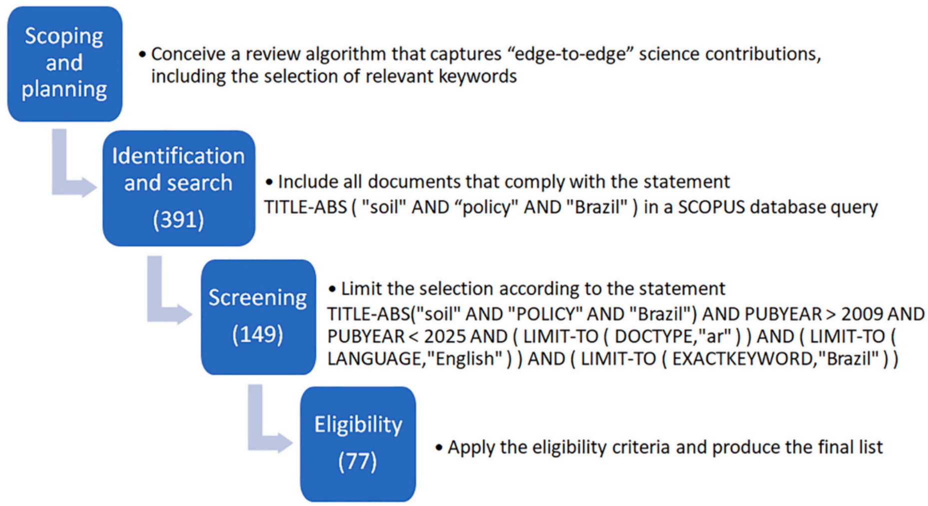

Fig. 1. PRISMA workflow applied to the review of articles published about soil conservation and promoting policies in Brazil between 2010 and 2023, following all the scope, screening and eligibility criteria.

Table 1
Summary of PRISMA results with additional information in the text. The Nr. values represent the number of articles included in the review per sub-topic.

Nr	Topic	Sub-topic	State(s)	Biome(s)	References
6	Geology-land use-soil property nexus	Geology - soil property nexus	São Paulo; Minas Gerais; Rio Grande do Norte; Paraíba; Rio Grande do Sul		Mendes and Demattê, 2022; Silvero et al., 2019; de Souza et al., 2015; Williams Araújo do Nascimento et al., 2021; Pott et al., 2023; Coblinski et al., 2021
2		Land use - soil property nexus	Amazonas	Cerrado; Amazon	Roitman et al., 2018; Lima and Vieira, 2013
4		Land use change - soil property nexus	São Paulo; Mato Grosso; Maranhão	Amazon; Cerrado	Calaboni et al., 2018; Spera et al., 2014; Celentano et al., 2017; dos Santos Rotta and Zuquette, 2021
5		Systemic approaches to environmental vulnerability and landscape restoration	Cerrado biome states; São Paulo; Parana	Atlantic Forest; Cerrado	Campos et al., 2021; da Silva et al., 2015; Manfré et al., 2013; Silva et al., 2023; Toledo et al., 2018
2	Soil degradation	Indicators of soil degradation	Piauí; São Paulo		Almeida-Filho and Carvalho, 2010; Nascimento et al., 2022
6		Quantification of soil losses caused by land use change	Cerrado biome states; Paraíba	Atlantic Forest; Cerrado; Caatinga	Couto et al., 2019; Ditt et al., 2010; Fonseca et al., 2022; Gomes et al., 2019; Salomão and Silva, 2022; Silva et al., 2018
2		Soil losses as proxies of environmental impact (reservoir siltation)	São Paulo; Minas Gerais		Lense et al., 2023; Lopes et al., 2022
1		Soil loss studies as contributors of Payments for Ecosystem Services schemes	Federal District		Lima et al., 2013
3		Geogenic contamination (quality reference values)	Southern states of Amazon region; Piauí; Pernambuco	Amazon	do Nascimento et al., 2018; Landim et al., 2022; Nascimento et al., 2019
5		Anthropogenic contamination	National; Piauí; Rio Grande do Norte; São Paulo; Rio Grande do Sul	National; Cerrado	de Menezes et al., 2020; Brito et al., 2020; Marinho et al., 2022; Leon et al., 2020; Silva et al., 2020
4	Soil carbon	Carbon stocks	Rio Grande do Norte; Paraíba; Pernambuco; Federal District; Minas Gerais	Caatinga; Cerrado	Althoff et al., 2018; Araújo Filho et al., 2018; de Sant-Anna et al., 2017; Morais et al., 2020
7		Carbon dioxide emissions	National; Sergipe; Pará; Mato Grosso do Sul; São Paulo; Parana	Atlantic Forest; Cerrado	Fernandes et al., 2020; Figueiredo et al., 2017; Schaldach et al., 2017; Machado et al., 2017; van der Hilst et al., 2018; Chaddad et al., 2022; Ruiz et al., 2023
1		Carbon dioxide sequestration (organic and inrganic pools)	São Paulo		Rosa et al., 2022
9	Soil management	Sustainable agriculture	National; Cerrado biome states; Legal Amazon states; Mato Grosso do Sul	National; Cerrado	Franco-Moraes et al., 2019; Bezerra et al., 2022; Souza et al., 2022; Cabral, 2021; de Amorim Júnior et al., 2022; Lucas et al., 2023; Martini et al., 2015; Medeiros et al., 2021; Ofstehage and Nehring, 2021
4		Sustainable cattle ranching	Mato Grosso do Sul; Pará		de Oliveira Silva et al., 2017; Kruger et al., 2022; Rufin et al., 2015; Silva et al., 2017a, 2017b
5		Sustainable ethanol production from sugarcane	National; São Paulo		Granco et al., 2019; Turetta et al., 2017; Martini et al., 2018; Ferreira Filho and Horridge, 2014; Gallardo and Bond, 2011
5	Soil and land use policies	Conservation of soil	National; Minas Gerais		Klingen et al., 2012; Polidoro et al., 2021; Rittl et al., 2015; Stuchi et al., 2021; Zolin et al., 2014
3		Integrated production systems	São Paulo; Maranhão; Acre; Rondônia, Mato Grosso; Pará		Cortner et al., 2019; de Souza Filho et al., 2021; Loch et al., 2021
3		Land use transitions	São Paulo; Bahia; Goiás	Atlantic Forest	Costa Coutinho et al., 2017; Oberling et al., 2013; R. F. B. Silva et al., 2017a, 2017b

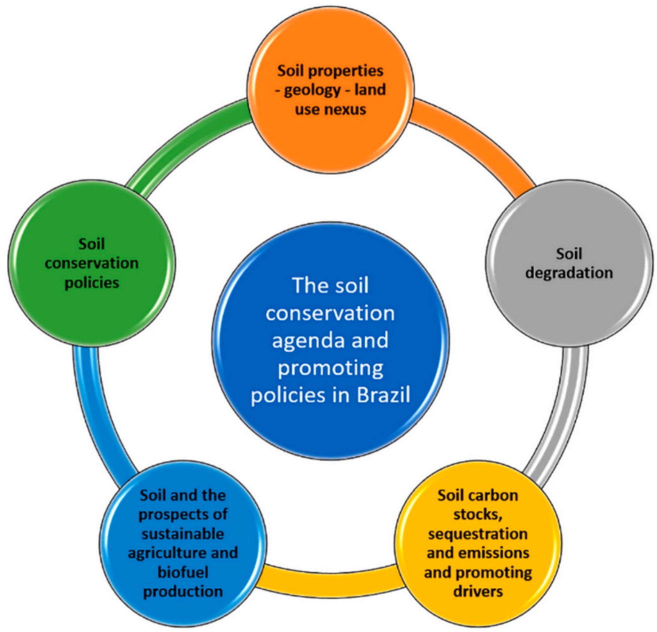

Fig. 2. Topics addressed in scientific literature focused on the Brazilian soil conservation agenda and promoting policies, as per the results of PRISMA survey.

Fig. 3. Word cloud based on word counts from the 77 article abstracts.

the most basic of characterization, to the most practical of management, to the most abstract of policy guiding and legal enforcement. More importantly, together they make us trust on a decision-making chain supported and well-articulated with scientific models and not only with circumstantial discourse, which we believe is the best insurance of soil conservation.

4.1. Soil properties, geology and land use nexus

Soil is developed from weathering of parent materials, namely igneous, metamorphic and sedimentary rocks, while land use can be an anthropogenic cause of soil property changes. Despite of being a classic subject in soil science, the chemical fingerprint of bedrock and land use on soils is still a topic of scientific research, as detailed in the reminder of this section and illustrated in Fig. 4. Besides the academic scientific research discussed below, a landmark initiative concerning soil in all dimensions cannot be omitted because of its strategic importance for land management in Brazil. We are talking about the PronaSolos – Programa Nacional de Levantamento e Interpretação de Solos do Brasil (https://www.embrapa.br/en/pronasolos), recently launched. This is a long-term project that will gather for the next thirty years many partnership institutions with the purpose of mapping soils and interpreting soil data across the country, with the detail of 1:25,000 and 1:100,000 scales.

The recent investigation on geology – soil property relationships has focused on techniques that can be used to scan large areas with low cost, such as digital soil mapping or visible–near infrared–shortwave infrared (VIS–NIR–SWIR) field reflectance spectroscopy. Digital soil mapping is a recent framework in soil science that uses quantitative models (like deterministic, stochastic or artificial intelligence methods) to predict soil attributes, properties and classes while taking soil formation factors into account (like geology, topography or climate). The models are derived from georeferenced field soil samples and linked with landscape variables compiled from remote sensing data sources (Minasny and McBratney, 2016). The VIS–NIR–SWIR technique (Zahir et al., 2022), on the other hand, uses the energy from the visible, near-infrared and shortwave-infrared wavelength regions from the electromagnetic spectrum (0.4 – 0.7, 0.7 – 1.0 and 1 – 2.5 μm, respectively) to analyze minerals, namely those that comprise the inorganic compartment of soil. This is possible because different minerals present distinctive spectral signatures composed of specific energy absorption peaks within the above quoted wavelength regions. A couple of recent studies performed digital soil mapping as key objective, namely in the state of São Paulo (Mendes and Demattê, 2022; Silvero et al., 2019). Other studies used digital soil mapping as tool to reach an ultimate goal, namely geochemical fingerprinting to unfold geology – soil property relationships. In that context, it is worth mentioning a few cases. The first example relates with the metal fingerprinting of mining areas (de Souza et al., 2015). The study involved characterizing and mapping quality reference values of metal (loid)s outside mined areas, with the purpose of improving the monitoring of soil contamination in mined areas. To accomplish the goal, the authors measured the concentrations of a number of metals and metalloids (Al, As, B, Ba, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Sr, V and Zn) across the entire state of Minas Gerais, spanning a diversity of pedological and geological contexts. In keeping with the results of a cluster analysis applied to the dataset derived from those chemical analyses, four geochemically different geologic contexts within the state were identified, characterized by contrasting metal(loid) concentrations. These were the Iron Quadrangle, where the high metal(loid) concentrations were related with the presence of sulfides in gold-bearing rocks and iron mineralization in various rocks (e.g., itabirites); the Serra Geral Formation, where the high metal(loid) concentrations reflect the presence of continental flood basalts enriched in phenocrysts of pyroxene, plagioclases and opaque crystals such as titanomagnetite or ilmenite; the Mantiqueira province, with lower than the Iron Quadrangle and Serra Geral Formation concentrations; and the Neoproterozoic and Cretaceous sandstones of Minas Gerais, where the absence of ores leads to low metal (loid) concentrations. The clustering results led the authors to question the CONAMA's Resolution no. 420, dated from 28 December, 2009, which defines a single Quality Reference Value for each chemical element, because unique values cannot capture the soil's geochemical diversity. Instead, according to de Souza et al. (2015) the Quality Reference values should be linked to dominant pedogenic provinces settled on the main geological provinces of all states in the country. The second example has echoed from a public health concern and relates with the mapping of selenium (Se) deficiency in soils, and hence in crops, which can propagate to animals and humans through the food

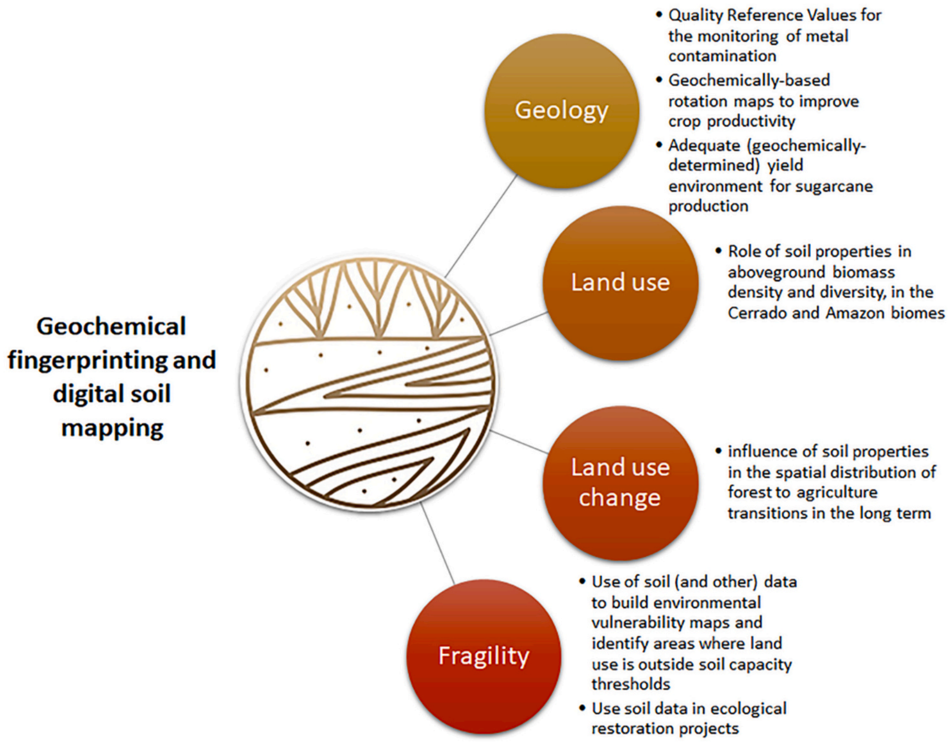

Fig. 4. Key aggregated outcomes of studies addressing geology – soil property, land use – soil property, land use change – soil property relationships, as well as soil data-based fragility.

chain (Williams Araújo do Nascimento et al., 2021). The health concern derives from risks that are known to relate with Se malnutrition, such as oxidative damage or various chronic diseases, as highlighted in the study. The work done in that study covered the states of Rio Grande do Norte and Paraíba and was eventually the most wide-ranging attempt to characterize and map selenium in Brazil to date, providing Se concentrations for a variety of soils and parent materials and a subside to health authorities. Besides the health concern, the authors justified the research because the spatial distribution of Se across Brazil is poorly understood, especially the roles of parent materials and climate-soil interactions. The results indicated higher concentrations in soils weathered from sedimentary rocks (0.45 mg/kg), relative to those altered from igneous rocks (0.36 mg/kg). They also related higher concentrations with more intense weathering of parent rocks, but more importantly than everything else the study outcomes distinguished humid coastal regions with larger Se concentrations (0.3 – 1.7 mg/kg), where the annual precipitation ranges from 700 to 1700 mm, from semiarid inland regions with smaller concentrations (0.1 – 0.25 mg/kg), where precipitation varies from 500 and 700 mm. Put another way, the authors interpreted the spatial distribution of Se as being mostly controlled by climate, namely though wet deposition. A critical result refers to the relatively large area occupied with soils where Se is deficient (0.13 mg/kg) and for that reason a potential source of health problems to humans. In the sequel of relating deficient Se concentrations (and hence disease probability) with the semiarid climate, the authors alerted for the 24 million people living in the semiarid region of northeastern Brazil, who can be exposed to Se-related health problems. The last couple of studies used as reports of geochemical fingerprinting and digital soil mapping in this review relate with using these techniques for crop monitoring (Mendes and Demattê, 2022; Pott et al., 2023), i.e. as subside to the management of farming. In the first case, Pott and co-workers used previously published crop data at field scale derived from a satellite-based data fusion model, to generate a rotation map layer for the Rio Grande do Sul state. The benefits of crop rotation for soil are well known and include improved soil aggregation, root penetration and aeration, as well as enhanced nutrient availability and restored soil organic carbon that promotes biologic activity and overall soil health. But the question posed by the authors was if a rotation map could help explaining crop productivity variations in the state, namely of soybean, corn and rice, besides shedding light over the factors that control crop rotation patterns in the region. The results pointed to a yield penalty between 20 and 65% for soybean areas not practicing crop rotation, which is noticeable. In the second case, the authors Mendes and Demattê used geochemical fingerprinting to set up an adequate yield environment for sugarcane production in São Paulo state, among other issues. The results highlighted aluminum saturation at the least revolved soil layer as key attribute to classify the yield environments, which could be used by farmers to manage their lands more efficiently while allocating harvest blocks. The final example of chemical fingerprinting applied to the soil science refers the use of VIS–NIR–SWIR reflectance spectroscopy to identify minerals in subtropical soils (Coblinski et al., 2021). The study was carried out in the state of Rio Grande do Sul, and was based on samples collected from Rhodic Acrisols, Xanthic Alisols, Xanthic Acrisols and Dystric Regosols, which were derived from granitoids and alluvial deposits. A FieldSpec-Pro spectrometer (Analytical Spectral Devices) was used to obtain the reflectance spectra. The results were promising because different minerals were detected in different wavelength regions: 430–460 nm for goethite 535–585 nm for hematite, 2204–2226 nm for kaolinite, 2344–2372 for illite and 2372–2270 nm for chlorite.

The land use – soil property nexus has also been addressed in various scientific publications. For example, (Roitman et al., 2018) used multiple regression models to demonstrate the role of soil texture in the variation of Cerrado's biome aboveground biomass density. The study involved 77 sites, 893 plots and 95,484 trees, distributed among 13 Cerrado ecoregions. The measurements of aboveground biomass varied considerably among ecoregions (8.8 – 42.2 ton/ha), among sites within the same ecoregion (4.8 – 39.5 ton/ha), and among plots within the same site (24.3 – 69.9 ton/ha). These wide ranges likely reflected regional climate and local physiographic (e.g., soil texture, topography) heterogeneity, the reason why the regression models included explanatory variables such as ecoregion, soil sand content and soil clay content, which explained 42, 11.5 and 7.4% of aboveground biomass variance, respectively. The results for sand content were unexpected in the authors' view. Higher sand content in the soil is usually associated with lower water retention because of sandy soils enhanced drainage. The authors expected a negative correlation of this explanatory variable with the aboveground biomass density, because water is key to biomass growth. To explain the striking outcome, the authors argued that sites with high sand content were located close to the Amazon, where precipitation is high and capable of swamping the drainage effect. They also recalled that Cerrado's vegetation roots often have roots that penetrate deep into the regolith reaching the water table, and assess groundwater that way even in the drought season. Overall, the results are useful to manage reforestation projects considering the soil type that prevail in the studied regions, and hence can be important to regional land use planning. Another study that also investigated the relationship between vegetation cover and soil properties, and hence can assist landscape planning through sustainable successful reforestation projects, was carried out at the Tropical Silviculture Experimental Station of the National Institute of Amazonian Research, located in Manaus, state of Amazonas (Lima and Vieira, 2013). The analysis involved 1272 tree specimens of 217 species and 54 botanical families, distributed among 3 forest stands. In this case, an association based on Canonical Correspondence Analysis was established between the species composition and the environmental variables percentage of open canopy and the soil's aluminum and nitrogen content, pH and base saturation.

Some studies bearing on the land use – soil property relationships have focused on land cover changes instead of land covers themselves. The studies of Calaboni et al. (2018), (Spera et al., 2014), (Celentano et al., 2017), and (dos Santos Rotta and Zuquette, 2021) can be included in that research line, and they all contributed with important insights to soil conservation and land use policies, considering the key deforestation *versus* soil property links revealed in those works. In the first case, the authors studied historical patterns and potential drivers of forest transitions in the state of São Paulo in the 1960 – 2006 period, and noted both forest losses and forest gains. As regards the influence of soil properties in these changes, the study highlighted the effect of water retention capacity on forest losses before 1996. This soil property is key to agriculture suitability and drove forest losses in the 1960 – 1996 period, because deforestation was the pathway to expand the agriculture frontier in that era and the expansion has naturally occurred towards higher suitability lands, namely those with high water retention soils. The study of Spera et al. (2014) has also emphasized the role of water in the routes of land use change. These authors investigated the occupation of land with soybean cultures in the state of Mato Grosso in the 2001 – 2011 period, including expansion, abandonment and frequency of harvest (single or double cropping). As indicated in the study results, the profile of abandonment from 2002 to 2010 moved towards lower, more sloped and drier lands, meaning that soil water was a criterion in the farmers decision. The third example devoted to the land use – soil property nexus, of Celentano and co-workers, analyzed forest to agriculture conversions but was focused on the degradation of riparian forests along stretches of Pepital and Grande rivers located in the Maranhão state and Amazon biome. The main purpose was to set up a relationship between vegetation structure (e.g., canopy opening), which can be monitored trough remote sensing techniques with no difficulty, and soil properties that provide vital ecosystem services but nevertheless are less suited for that kind of surveillance. A successful result in that regard would help modeling large scale losses of soil quality and related ecosystem services, based on the spatio-temporal evolution of vegetation structure. The experimental design involved the classification of test sites according to four degradation levels: the very high degradation level comprised sites without trees and canopy cover $< 10\%$; the high degradation level sites with 7m-high trees and canopy cover in the 10 to 50% range; the moderate degradation level sites with 15m-high trees and canopy cover in the 50 to 00% range; and finally, the low degradation level sites with trees taller than 15 m and canopy cover exceeding 80%. The results showed significant variations in soil properties, expressing overall quality loss. Firstly, organic carbon decreased from 27.6 to 14.8 mg/kg, on average, from very low to very high degradation sites. On the other hand, average total porosity decreased in the same sense, from 62.8 to 49.7%, being accompanied by expressive decreases in water content and infiltration rates, from 19.7 to 3.6% and 62.5 to 5.4 mm/s, respectively. The tree height and basal area were among the vegetation indicators best suited to describe soil quality losses in the studied area. The study of dos Santos Rotta and Zuquette (2021) is the fourth example selected here to document relationships between land use changes and soil property changes in Brazil. These authors used historical data (aerial photographs and satellite images dated back to 1972), to identify and map spatial and chronological sequences of land use changes in the Ribeirão do Pinheirinho basin (area: 40 km^2) located in the central part of São Paulo state, from native vegetation composed of Cerrado and riparian forests, to sugarcane fields, pine and eucalyptus plantations, and pastures for livestock production. They used 13 transects that intersected all sub-basins and geological units (sandstones, claystones and siltstones from the Itaqueri Formation; basalts from the Serra Geral Formation; and sandstones from the Botucatu Formation) to refine the spatial sequences. And finally, they characterized 150 sites along the transects, where they also executed *in situ* infiltration and penetration strengths tests, and collected undisturbed and disturbed samples to be analyzed in the laboratory for physical parameters (e.g., grain size distribution, density, porosity), mineralogy, presence of macropores, hydraulic conductivity and erodibility. This very detailed survey allowed high-resolution detection of landscape changes and concomitant effects on soil, which briefly were: (a) decrease of root depth in the transition from natural vegetation to sugarcane plantations, which affected water flow and storage; (b) exposure of saprolite layer at the surface, destruction of saprolite layer structure, compaction and formation of crust layers caused by the use of heavy machinery. Taken together, these anthropogenic interferences had significant effects on the soil's erodibility, hydraulic conductivity and infiltration capacity, increasing the first and decreasing the other two, and propagated indirect consequences such as the dry-off of many springs because of reduced recharge.

A third research branch dedicated to the analysis of geology – land use – soil property associations comprised systemic approaches to environmental fragility with a focus on the (in)adequate use of soils, and studies on environmental restoration to improve soil fertility (Campos et al., 2021; da Silva et al., 2015; Manfré et al., 2013; Silva et al., 2023; Toledo et al., 2018). This type of studies is key to land use allocation plans, which are sought to be predicted in municipal land use policies and embedded in the corresponding land management plans, and hence are scientific contributions to be seen as references in that regard. Environmental fragility models like those used in the studies of Campos et al. (2021) and Manfré et al. (2013) are two-stage methods that in a first phase use multicriteria analysis to estimate the environmental vulnerability of a region based on the spatial distribution of parameters such as topography (slope classes), geology, soil cover and rainfall. Initially, the parameters are recast as vulnerability indicators (e.g., for topography, slopes $< 6\%$ indicate low vulnerability, rated as 1; between 6 and 12% indicate medium vulnerability rated as 2; and so forth, until slopes larger than 30% that indicate very high vulnerability and are rated as 5) and then global vulnerability is obtained through the weighted sum of those indicators. The larger the vulnerability is, the larger is the potential for soil erosion and the deeper must be the concern about using the land according to its capacity to avoid the amplification of erosion processes. In the second phase, another multicriteria analysis is used to assess environmental fragility based on the previously determined vulnerability and an environmental indicator based on land use. The two studies had similar foci but presented nuances. The work of Manfré et al. (2013) was conducted in the Paiol (area: 82 km^2) and Sorocabuçu (area: 83 km^2) hydrographic basins, which are located around the Ibiuna city in the state of São Paulo. The key objective was to zone the basins according to environmental fragility and prioritize interventions where the overlay of fragility and actual land use maps raised concerns. The highest concerns were flagged for very high vulnerability areas that should be covered with native vegetation but instead had the soil exposed to the action of erosive agents or were used for agriculture or livestock pasturing. Globally, these vulnerable areas represented 16.24% of Paiol and 35.8 of Sorocabuço basins. The conflict between environmental vulnerability and actual land use made the authors prioritize these areas for ecological restoration projects. The work of Campos et al. (2021) was developed on the Caratinga River basin (area: 3,228 km^2), which is located in the state of Minas Gerais being a right bank tributary of Doce River. In this case, the authors mapped land use capacity, besides the environmental fragility, and delineated underused, ideally used and overused areas within the studied basin through comparison between the two maps. The determination of land use capacity was based on a previously published method that hinges on parameters such as soil type and fertility, depth and internal drainage of soil profiles, flood risk and topographic slope. The environmental fragility map pointed a substantial coverage (61.3%) by the high fragility class, mostly occupied with pastures, and a minor coverage (2.1%) by the very high class essentially characterized by exposed soil. The bad news was that a large portion of pasture land in the Caratinga River basin (79.7%) is overused, meaning that the use exceeds the land capacity and hence that amplified susceptibility to erosion and soil degradation is expected in those areas. In both studies, environmental fragility was the alert for the need to restore areas of inadequate land use.

Ecological restoration was the target of various studies from the recent past, with a few examples being carried into this review (da Silva et al., 2015; Silva et al., 2023; Toledo et al., 2018). The work of da Silva et al. (2015) was rather localized and focused on specific indicators of ecological restoration, namely on the community composition of fungi in soils. The authors studied 2 natural and 2 revegetated (previously mined) areas located in the municipality of Mataraca (state of Paraíba) and representing the so-called “restinga” vegetation usually present in coastal areas on the borderline of Atlantic Forest biome. The results indicated an improved richness in the re-vegetated areas, which was unexpected but likely explained by the combined effect of soil structure disruption during the mining phase, and the introduction of fungi along with the seed-enriched substrates used during the re-vegetation phase. The work of Silva et al. (2023), on the other hand, addressed ecological restoration from a rather ample viewpoint. The authors investigated 93 active and 15 abandoned pastures distributed across the Cerrado biome, which covers the states of Piauí, Maranhão, Bahia, Tocantins, Minas Gerais, Goiais, Federal district (Brasília), Mato Grosso, São Paulo, Mato Grosso do Sul, and a little of Parana. Among the active pasture sites, 63 were originally savannas and the other 20 were originally forests. The specific objective was to assess the roles of various parameters in the regeneration potential of native plants from that biome. The parameters comprised biophysical properties such as soil type and its percentage of sand, terrain slope, water deficit, pasture age and the time since the last fire or renewal; the percent occupations with native vegetation and exotic grass within a 5-km buffer from the site; the implementation of management practices such as herbicide and fertilizer use; and the time since the abandonment. Then, the authors used structural equation models and generalized multiple linear regression models to predict the richness of trees recruits, as well as the percentage of native vegetation cover in the studied sites, considering the contributions of all aforementioned parameters. The results for active pastures that were originally savannas related richness with lower density of adult trees, lower use of fertilizers and lower exotic grass cover, while the native cover was related with pasture age and lower occupation with exotic grass. For the pastures that were originally forests, the models related richness with shorter periods after the last fire or renewal, more intensive use of fertilizers and herbicides, and sparser cover with exotic grass. The native cover, on the other hand, was related with sparser cover with exotic grass, shorter periods after the last fire but longer periods after the last renewal. In the abandoned pastures, factor time was predominant in all cases. Taken the modeling results altogether, it becomes evident how complex regeneration can be in this biome and hence how cautiously regeneration projects need to be implemented. In general, the results allowed to conclude that intensity of management coupled with the competition between native vegetation and exotic grasses for space, mediated by biophysical variables, determine the potential of Cerrado biome regeneration. Undoubtfully, this synthesis is of paramount importance and should be transposed to land use policies focused on the Cerrado biome. The need to evaluate critically the implementation of restoration projects was also the purpose of Toledo and co-workers (Toledo et al., 2018) who analyzed restoration efforts in the entire state of São Paulo. The major points raised by the authors hinge on the circumstance that the state has less than 18% native vegetation cover, which makes regeneration promoted by any project very challenging. One point derived from this scenario is that the mean distance of a native vegetation stand to its closest neighbor is 2.5 higher than the critical threshold of 200 m thought capable to grant spontaneous recovery and effective management. Another point relates with the cost of recovering highly degraded soils and landscapes, which can be exacerbated by the full recovery time because it can be of decades. Again, these are fundamental metrics in land use policy and should be considered at state level.

4.2. Soil degradation

The previous section reviewed studies where the authors were preferably interested in the diagnosis of soil properties as they vary among geological or land use contexts or in the course of land use changes including those resulting from restoration projects. A common sense retrieved from these studies is that inadequate use or improper manage can lead to soil degradation, namely soil erosion, soil contamination or other forms of degradation. Another common sense was that land use policies and land management plans both benefit from these scientifically supported results and therefore should incorporate them if that is not the case already. The outcomes from Section 4.1 (an “edge” in this review) are also the background knowledge of studies discussed in this section (a frontier “edge”), i.e. the link thrown from the previous section. Thus, in the current section, a number of examples are reviewed from the scientific literature where the authors quantified land use-related impacts to soil, while the key outcomes are charted in Fig. 5.

Soil erosion is a natural process that can be amplified through climate change and(or) human interferences on the landscape, leading to land degradation and ultimately to desertification. This has been documented widely in the past and keeps the attention of researchers in the recent literature about soil erosion assessment (Borrelli et al., 2021), probably because climate change is a hot topic in governmental and institutional agendas and the above-mentioned interferences continue expanding worldwide. Some studies in Brazil assessed land degradation from comparison of exposed soil areas detected in satellite images captured with a substantial time lag. For example, in the work of Almeida-Filho and Carvalho (2010) taking place in the Gilbue’s region (3,830 km^2), state of Piauí, the authors reported that exposed soil interpreted from Landsat images raised from 516 to 630 km^2, in the dry season (April – September), and from 443 to 603 km^2 in the rainy season (October – March), in two decades (1986 – 2005 period). A more elaborated study covered the entire state of São Paulo and defined a soil degradation index (SDI) based on the clustering of remote sensed and field data spanning the 1985 – 2020 period and the following attributes (Nascimento et al., 2022): bare soil frequency, topsoil (0 – 20 cm) attributes (clay content, cation exchange capacity, organic matter) obtained from thousands of published literature data, terrain data (e.g., hillside slope and length, land surface temperature), climatic (precipitation) and land use or cover records. The SDI was checked against

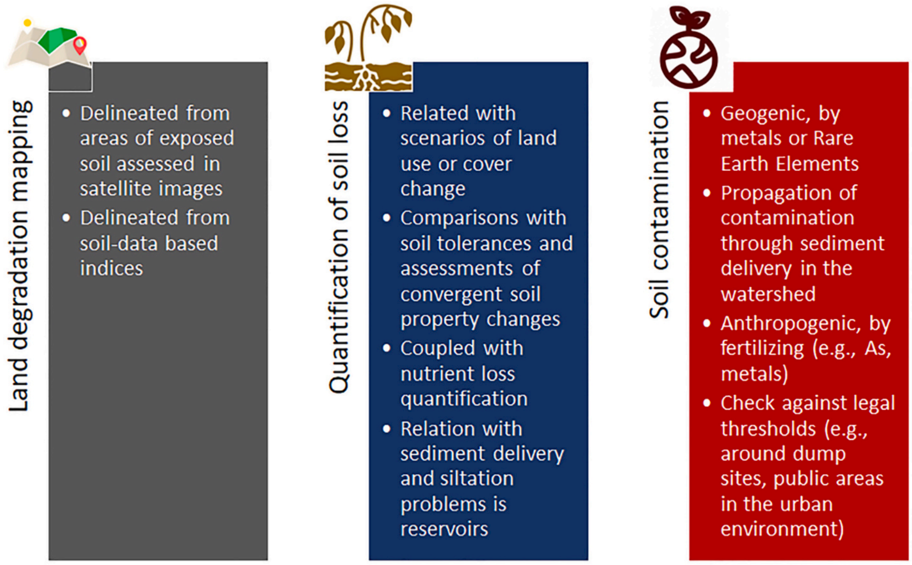

Fig. 5. Key aggregated outcomes of studies addressing soil degradation.

organic matter with very good results expressed as clear association between increasing degradation and organic matter decline. The results highlighted the high to very high SDI estimated for the western and central parts of São Paulo state, as well as the need to implement land management plans more effectively to reverse the very preoccupying situation. The A major share of land degradation-related studies, however, dedicated efforts to quantify soil losses as function of land use conversions (Couto et al., 2019; Ditt et al., 2010; Fonseca et al., 2022; Gomes et al., 2019; Salomão and Silva, 2022; Silva et al., 2018). For example, while working in the Cachoeirinha stream basin (14.73 km^2) located in the state of São Paulo, Couto et al. (2019) used the Universal Soil Loss Equation (USLE) to estimate rates of soil removal under three land use scenarios: one describing the current land use, a second evaluating the protective role of native vegetation and the last forecasting expansion of sugarcane areas in the basin. The authors also compared soil losses with tolerable thresholds defined for relevant soil types to assess denudation rates. The geology of Cachoeirinha stream basin is characterized by sedimentary rocks, mostly sandstones and mudstones, covered with oxisols and ultisols with soil tolerances to erosion of 12.6 and 9.1 t/(ha·yr), respectively. Land is extensively occupied with sugarcane plantations, which are expected to grow in the future to meet increasing ethanol production demands. Under the protective cover of native vegetation (baseline scenario), the simulated soil losses varied between 0.01 and 0.4 t/(ha·yr) (average: 0.03 t/(ha·yr)). This was likely the erosion window in the entire basin before the land use conversions that started with coffee plantations in 1929. Under the current land use, the erosion rates were estimated in the 0.1 – 40 t/(ha·yr) range (average: 3.5 t/(ha·yr)), meaning a nearly 117-fold increase in the removal of soil relative to the baseline scenario. In this case, the area of Cachoeirinha stream basin affected by intolerable losses was 17%. This is bad news, but the continued expansion of sugarcane in the future was predicted to increase soil losses even further, reaching the 0.1 – 58 t/(ha·yr) range (average: 12.6 t/(ha·yr)) and a 420-fold increase with reference to the base scenario and a 3.6-fold increase relative to the current land use. The area of intolerable soil loss would also exacerbate to 57%. Again, the need to implement proper management practices was the main alert to report. The work of Ditt et al. (2010) was also dedicated to USLE-based soil loss modeling and was likewise developed in the state of São Paulo, but covered the 188 watersheds (76.24 km^2) that surround the Atibainha Reservoir. Land use in these catchments is currently characterized by a mosaic of Atlantic Forest remnants (46%), pastures (27%), eucalyptus plantations (10%) and other uses (17%). The anticipation of soil erosion was also based on land use change scenarios, but now the changes were from the current land use to100% pastures, 100% native vegetation or 100% eucalyptus plantations, tested in separate. The modelling results indicated a current soil loss of 1,037 t/yr in the studied area, that will likely rise to nearly 1,500 t/yr if all the area is converted to pastureland. If, otherwise, eucalyptus or native vegetation replaces the pastures, the expected soil loss reduces to 39 and 9 t/yr, respectively. The mitigation in these two cases would be remarkable and hence worth of consideration in future landscape plans developed for the area. The relationship between soil erosion and deforestation was investigated in detail in states occupied with the Cerrado biome, in the works of Fonseca et al. (2022) and Gomes et al. (2019). The work of Fonseca and collaborators reviewed soil loss data from previously published studies, which encompassed 10 sites distributed per 5 states (São Paulo, Minas Gerais, Distrito Federal, Mato Grosso and Mato Grosso do Sul). Areas of bare soil stood out as more eroded, with soil losses around 24.97 t/(ha·yr), and they were larger than the estimated soil tolerances (9.65 t/(ha·yr)). In decreasing order, the areas of conventional agriculture (7.13 t/(ha·yr)), conservation agriculture (2.20 t/(ha·yr)), eucalyptus plantations (0.20 t/(ha·yr)), pasture (0.20 t/(ha·yr)) and Cerrado vegetation (0.08 t/(ha·yr)), all experienced soil losses smaller than the tolerances for average runoff conditions. The key subside to land use policy was that preservation of vegetation cover is essential to control erosion, a common-sense perception validated with scientific evidence in this spatially ample study. The work of Gomes and collaborators extended the analysis of soil erosion in the Cerrado biome to include nutrient losses, while providing a temporal view over these losses in a decade (2000 – 2012 period). The study covered all states with Cerrado biome vegetation (Bahia, Goiás, Maranhão, Minas Gerais, Mato Grosso do Sul, Mato Grosso, Piauí, Paraná, São Paulo and Tocantins) and the key findings encompassed the recognition of a soil loss increase caused by agriculture expansion, from 10.4 t/(ha·yr) in 2000 to 12.00 t/(ha·yr) in 2012. In the same period, severely eroded areas increased from 3 Mha to 5.7Mha, while losses of nitrogen were 13.2 to 25.9 and of phosphorus 13.1 to 23.1 times higher in these areas than in moderately eroded ones. The relationship between soil loss and deterioration of soil health was also tackled in the work of Salomão and Silva (2022), who worked in two sub-basins (B1 and B2) of Sapiantã watershed (area: 39.3 km^2) located in the state of São Paulo, distinguished by the contrasting occupations of forests, pastures and anthropic areas. Pastures predominated (55.22%) in the B1, where the forests and anthropic areas represented 26.91% and 17.87%, respectively, while forests prevailed

(66.52%) in the B2, where pastures and anthropic areas represented 27.71% and 4.3%. The percentage of forest cover played a pivotal role in the estimated values of soil loss, because the B1 (with less forest) revealed 63% of basin area with low soil loss (< 10 t/(ha·yr)) while the B2 (with more forest) revealed 90%. Besides, in the B1, the areas with high soil loss (> 50 t/(ha·yr)) were located in the lower lands where the occupation by pastures dominated, while in the B2 no specific zoning was detected. The impact of soil erosion on soil properties was clear in B1. Here, soils became coarser (with more silt and fine sand) in the lower lands occupied with pastures relative to the higher lands (with more clay) occupied mostly with forests, while no differences were detected in texture across the B2. The soil' electrical conductivity was also different in the two catchments. The lower values observed in B1 were attributed to higher nutrient leaching from soils covering the pastures as well as to lower soil moisture caused by higher compaction in these areas. A final example worth of report about land use or cover changes and concomitant soil loss changes refers to a study carried on in the Monteiro municipality (area: 990.47 km^2) located in the state of Paraíba (Silva et al., 2018). This is a hot semi-arid region of Northeastern Brazil, characterized by average temperatures in the 25 – 30°C range uniformly distributed throughout the year, and by average rainfall around 700 mm/yr concentrated in the February – May period. The vegetation covering the municipal area comprises: (a) Tropophile caatinga high strand, which are woody savannas with dense cover mostly present in the highlands of steeper slope; (b) Tropophile caatinga middle slope, characterized by sparser woody vegetation with intense human-related changes; (c) Tropophile caatinga plain, represented by shrublands that occupy low altitude flat areas. The study's objective was to evaluate soil loss changes in the municipality in the 1987 – 2010 period, considering gains and losses of caatinga types coupled with the urban expansion and revegetation of bare land observed in that period, with the ultimate goal of evaluating the municipal land use management plans. The results highlighted the reduction of soil losses in the high strand areas, from 1.5 to 0.3 t/(ha·yr), because the vegetation cover in these steep slope high altitude areas raised from 225.1 to 275.1 km^2. An additional contribution to soil loss reduction in the municipality of Monteiro came from the revegetation of bare land that reduced its coverage from 64.8 to 22.7 km^2, with a correspondence in soil loss decline from 132.6 to 93.3 t/(ha·yr). The expansion of urban lands from 1.5 to 4.7 km^2 raised soil erosion in those areas, from 0.01 to 0.6 t/(ha·yr), but taken all land cover transformations together the global results for the municipality were a decline of soil loss from 9.67 to 2.67 t/(ha·yr) in the two decade timeframe. This seems an important outcome to acknowledge the local forest management authorities. Although representing the largest share, the study of soil losses in recent publications about Brazil was not restricted to soil conservation and management. Sometimes, soil losses in river basins were estimated to be used as environmental impact and management indicators, namely as reservoir siltation proxies (Lense et al., 2023; Lopes et al., 2022). For example, in the simulation work carried on the Jaguarí River basin (area: 2,204 km^2; São Paulo and Minas Gerais states), Lopes et al. (2022) estimated an average soil loss of 1.71 t/(ha·yr) and an average sediment delivery rate of 4.7%, using the USLE. The Jaguarí River has been dammed to store drinking water for the supply to São Paulo Metropolitan Region (MRSP) with 22 million people, the largest in Brazil and among the largest in the world. The Jaguarí reservoir is one among the five reservoirs that form the Cantareira System used to supply 46% of all the MRSP with 33 m^3/s. The results obtained for soil loss and sediment delivery rate are low but nevertheless represent a load to the Jaguarí reservoir of nearly 1000 t/yr. With this load, the useful life of Jaguarí reservoir was estimated in 63 years, which is not too much considering the regional importance of this water body and hence the need to keep it operational in the long term. The study of Lense et al. (2023) extended the soil loss and sediment delivery analyses to the entire Cantareira system and provided corresponding average values: 13 t/(ha·yr) and 6.2%, respectively. The average soil loss value estimated for the entire system is larger than the homologous value estimated for the Jaguarí River basin, but the sediment delivery rate is similar. The authors highlighted the presence of extensive areas (62%) of low soil losses, which they related with a predominance of forest cover (45%) where the soil losses were very low (0.1 t/(ha·yr)). A last purpose of soil loss studies that came across the current review was to propose (or not) schemes for the payment of ecosystem services at municipal scale, namely regulation services. In the Sarandi Experimental River Basin (area: 32.7 km^2) located in the Federal District, Lima et al. (2013) realized that USLE-derived soil losses were ≤ 1 t/(ha·yr) in nearly 90% of all the basin area. Besides, the areas with high susceptibility to erosion were concentrated in specific sectors and represented solely 5.2% Sarandi basin. In keeping with these outcomes, no justification was found to implement a PES scheme in the watershed, but maintenance of vegetation cover in the high susceptibility sectors were recommended to keep erosion rates below tolerable thresholds.

Soil contamination can also be natural (geogenic) or caused by anthropogenic activities. Research from the recent past has covered both causes and various publications had the focus on Brazil. Some of those studies were totally concerned on setting up quality reference values (QRV) for elements, to aid public policies on environmental monitoring and assessment. For example, the study of do Nascimento et al. (2018) proposed QRVs for various metals in soils from the Brazilian's Amazon biome, derived from sedimentary rocks. The dataset comprised 128 samples collected from the 0 – 20 cm layer and the proposed QRVs were (values in mg/kg): Cd (0.1), Sb (0.9), Ni (1.7), Cu (2.8), Pb (4.4), Zn (5.7), Cr (6.9), Mn (13.4), Fe (15.4) and Ba (16.5). A similar study was developed in the Piauí state, but the interest was on rare earth elements (Landim et al., 2022). The dataset included 243 samples collected from the 0 – 20 cm layer and the QRVs were set for the entire state and refined for the North-Central, Southeast and Southwest regions. The state's QRVs were (values in mg/kg): La (18.15), Ce (39.04), Pr (5.21), Nd (14.28), Sm (2.76), Eu (0.45), Gd (1.06), Tb (0.35), Dy (1.46), Er (0.63), Yb (0.54), Lu (0.25). A last example refers to the work of Nascimento et al. (2019) in the Ipojuca River basin located in the Pernambuco state. The authors' motivation was to determine background values and QRVs of thorium in soils weathered from granites but also track fluxes across sediments and water in the watershed. In that study, the dataset was composed of 25 sites and the QRVs derived therefrom were: 21 mg/kg and 86.3 Bq/kg. Other studies investigated sources of elements in soils (natural and anthropogenic fingerprints) with the purpose to alert the competent authorities for anthropogenic contamination. For example, the concentration of arsenic in soils was assessed across the entire territory of Brazil to detect eventual contamination related with fertilizing, besides the identification of natural drivers of spatial distribution (de Menezes et al., 2020). The dataset comprised 159 samples and encompassed a diversity of environmental conditions, namely soil type, biome, geology and climate. It also accounted sub-samples of soils collected from areas of native vegetation showing minimal anthropogenic disturbance (62 samples), and soils collected from agricultural fields where dressings of fertilizers have been applied (97 samples). The arsenic content in the first sub-sample ranged from 0.14 to 41.1 mg/kg and in the second sub-sample from 0.28 to 58.3 mg/kg. These results suggest an increase of arsenic in the agriculture soils related with the fertilizer inputs. This was an important outcome because As can propagate through the food chain and cause health problems, but the authors highlighted more the spatial variations of arsenic content related with natural drivers, supported in a cluster analysis. The variables standing out from this grouping exercise were the air temperature, and the contents in soil of arsenic, sand, clay, organic carbon (SOC) and TiO_2. The four groups resulting from the analysis were described with increasing arsenic concentrations related with the aforementioned variables, as follows: (G1: 2.24 ± 0.50 mg/kg) soils with a widespread distribution across the country, with coarser texture and lower SOC, higher temperatures and the lowest TiO_2; (G2: 3.78 ± 2.05 mg/kg) organic soils located in floodplains, with medium temperature and TiO_2; (G3: 7.14 ± 1.30 mg/kg) soils with a widespread distribution across Brazil, as those from G1, but with average values of all variables; (G4: 11.97 ± 1.62 mg/kg) soils located in the southeastern part of Brazil, with the highest values of SOC and TiO_2 and the lowest of sand. A second example we bring into this review to represent anthropogenic fingerprint studies was the work done in the Uruçuí-Preto watershed (area: 15,777 km^2) located in the Piauí state and representing an agriculture frontier in the Cerrado biome (Brito et al., 2020). The authors aimed to set on QRVs for heavy metals in sedimentary soils, and estimate enrichment factors to anticipate ecological risk of soil contamination. To accomplish the goal, they collected 62 soil samples from the topmost layer (0 – 20 cm), 30 from areas occupied with native vegetation and 32 from areas used for agriculture (mostly soybean) in the last 1 to 20 years. The analytical results and percentile analysis pointed to the following QRVs: (values in mg/kg, listed in decreasing order of concentration): Fe (18,700) > V (47.83) > Cr (43.44) > Ba (9.11) > Pb (2.73) > Ni (0.80) > Cu (0.74) > Zn (0.46) > Mo (0.34) > Cd (0.05) > Sb (< 0.0007) > Co (< 0.00008). These values were lower than those obtained for the agricultural soils, the concentrations of which are listed in the same order as the QRVs presented above for a direct comparison: Fe (27,067), V (65.26), Cr (55.66), Ba (5.21), Pb (2.69), Ni (0.912), Cu (2.14), Zn (3.56), Mo (1.32), Cd (0.06), Sb (1.55), Co (0.00008). The results indicate preferential accumulation of Sb, Zn Cu and Mo in the soils, related with continuous use of the soil for agriculture. A last group of studies developed in Brazil in the recent past and interested in soil contamination, reported specific cases of contamination with metals or organic contaminants. In one case, the contamination was related with heavy metal concentrations above the legal limits imposed by the CONAMA Resolution No. 420/2009, detected in 12 dump sites located in the Rio Grande do Norte state (Marinho et al., 2022), and hence represented a public health problem worth of denunciation. The dump sites were all inactive at the time of Marinho and co-workers' study, but have received waste during 4 to 50 years from construction sites and municipal slaughterhouses, among other sources. Following decommissioning, the dumpsites were covered with a soil layer, which were later used for agriculture or kept without any use, in which case spontaneous vegetation has occupied the place. The database included 24 soil samples collected from the 0 – 40 cm layer, 12 from the dumpsites and 12 from adjoining areas. The results indicate a clear increase of heavy metal concentrations in the dumpsite samples, relative to the non-dumpsite counterparts, namely (values in mg/kg, listed in decreasing order of percent increase): Cu (38.48 > 0.96; 40-fold increase), Ni (7.77 > 0.43; 18-fold increase), Pb (24.64 > 1.57, 16-fold increase), Cr (21.94 > 1.45, 15-fold increase) and Zn (42.03 > 4.3, 10-fold increase). The Zn concentrations were above the legal thresholds in all dumpsites. Other reports of soil contamination published in the scientific literature about Brazil relate with organic compounds. For example, the studies of Leon et al. (2020) and Silva et al. (2020) both reported risks of humans being infected with helminth larvae present in the excrements of cats and dogs, considering the common use of public and private places by people and their domestic pets. The difference among the two studies were mostly related on target areas: in the study of Silva et al. (2020), the samples were collected from soils in the vicinity of schools, clubs, public squares and residential condominiums of Votuporanga municipality located in the state of São Paulo, whereas in the study of Leon et al. (2020), the sampling was restricted to public squares located on the shore of Laranjal beaches, in the Laguna dos Patos, municipality of Pelotas, state of Rio Grande do Sul.

4.3. Soil carbon stocks, CO_2 emissions and sequestration

The dynamics of land use and cover changes interfere with the global geochemical cycles generating a diversity of impacts. The carbon cycle is central in that regard because, as highlighted in the previous sections, land use and cover changes modify the soil while, on the other hand, soil is the largest pool of terrestrial carbon on Earth (Wiesmeier et al., 2019). The interference of land use and cover changes with the carbon cycle occurs via carbon sequestration or emission, the balance of which determines the soil's carbon stock. Excessive carbon emissions deplete the soil from this vital element threatening provision of ecosystem services, at the same time that contribute to the enrichment of CO_2 in the atmosphere and drive greenhouse gas-related impacts such as extreme events (e.g., drought and floods). On the other hand, improved carbon sequestration can reverse this environmentally concerning pathway (Ramesh et al., 2019). A number of studies from the scientific literature have discussed carbon sequestration, emission and stocks in Brazil, the summary of which is presented in the forthcoming paragraphs and outlined in Fig. 6.

The research on carbon stocks compiled from recent scientific publications covering areas located in Brazil comprised quantitative assessments based on historical land use and cover changes and specific biomes (Althoff et al., 2018; Araújo Filho et al., 2018; de Sant-Anna et al., 2017; Morais et al., 2020). The studies of Althoff et al. (2018) and Araújo Filho et al. (2018) investigated carbon stocks under Caatinga biome contexts, which occupy nearly one million square kilometers of northeast Brazil's semiarid region. In the first case, the authors were working in the Seridó Ecological Station (Serra Grande do Norte, state of Rio Grande do Norte) and in the Tamandua Farm (Santa Teresinha municipality, state of Paraíba), where they used seven forest plots as field work sites. Part of these plots were "primary" caatinga forests (preserved for more than 50 years) and another part were secondary forests, meaning areas of caatinga vegetation that were converted into pastures or croplands a long time ago, abandoned some 20 years ago and naturally regenerated since then. The measured soil carbon stocks were 31.9 t/ha in the preserved plots and 23.2 t/ha in the regenerating plots (30% less), on average, a result that inevitably pushes full recovery of carbon stock in the topsoil (0 – 20 cm) to timeframes larger than two decades. The second study (Araújo Filho et al., 2018) was developed in the municipality of Floresta, state of Pernambuco, and the authors were also interested in evaluating the time needed by the soil to recover the stocks after the forests started natural regeneration. Seven sites were used in the field work, which were selected as function of time elapsed since forest cuts, namely 0.5, 6, 9, 12, 25, 50 and at least 80 years before the study time. A quadratic function was fitted to the topsoil carbon stock (SOC) *versus* time data using the equation ($SOC = 27.577 + 0.5158 \times time - 0.0040 time^2$; $R^2=0.95$), which provides SOC values around 27.577 t/ha for recently regenerating forests (0 years) and around 45.21 t/ha for "undisturbed" (not cleared for more than 80 years) forests. The equation is also capable of anticipating the full recovery of SOC stocks nearly 65 years after the beginning of forest regeneration. The papers of de Sant-Anna et al. (2017) and Morais et al. (2020) investigated soil carbon stocks, but centered the analyses in regions occupied with Cerrado biome vegetation. In the first case, Sant-Anna and collaborators conducted a long-term experiment (1991 – 2014) to test the effect on soil carbon stocks resulting from liming and fertilizing areas of native vegetation, as well as areas that were cleared from that cover and converted into pastures, continuous cropping lands and integrated crop-livestock systems. The study was conducted at the field station of Embrapa Cerrados Centre located close to Planaltina town in the Federal District. The average soil carbon stocks were close to 65 t/ha in the 0 – 30 cm layer and to 145 t/ha in the 0 – 100 cm layer, but strikingly neither differed much among native vegetation cover and the various treatments nor changed significantly overtime. The implications for land management are obvious, because the results anticipate low efficacy for restoration projects located in regions of Cerrado biome and focused on the recovery of soil carbon stocks through reforestation of areas previously used for agriculture or livestock pasturing. The second study, of Morais and co-workers, mapped soil carbon stocks across the entire Minas Gerais state, based on data from 176 sampling sites randomly distributed across 26 Cerrado forest remnants. The soil samples were collected from various layers until 1 meter depth. Besides quantifying the soil carbon stock, the authors wanted to explore potential relationships with environmental variables that could shed light

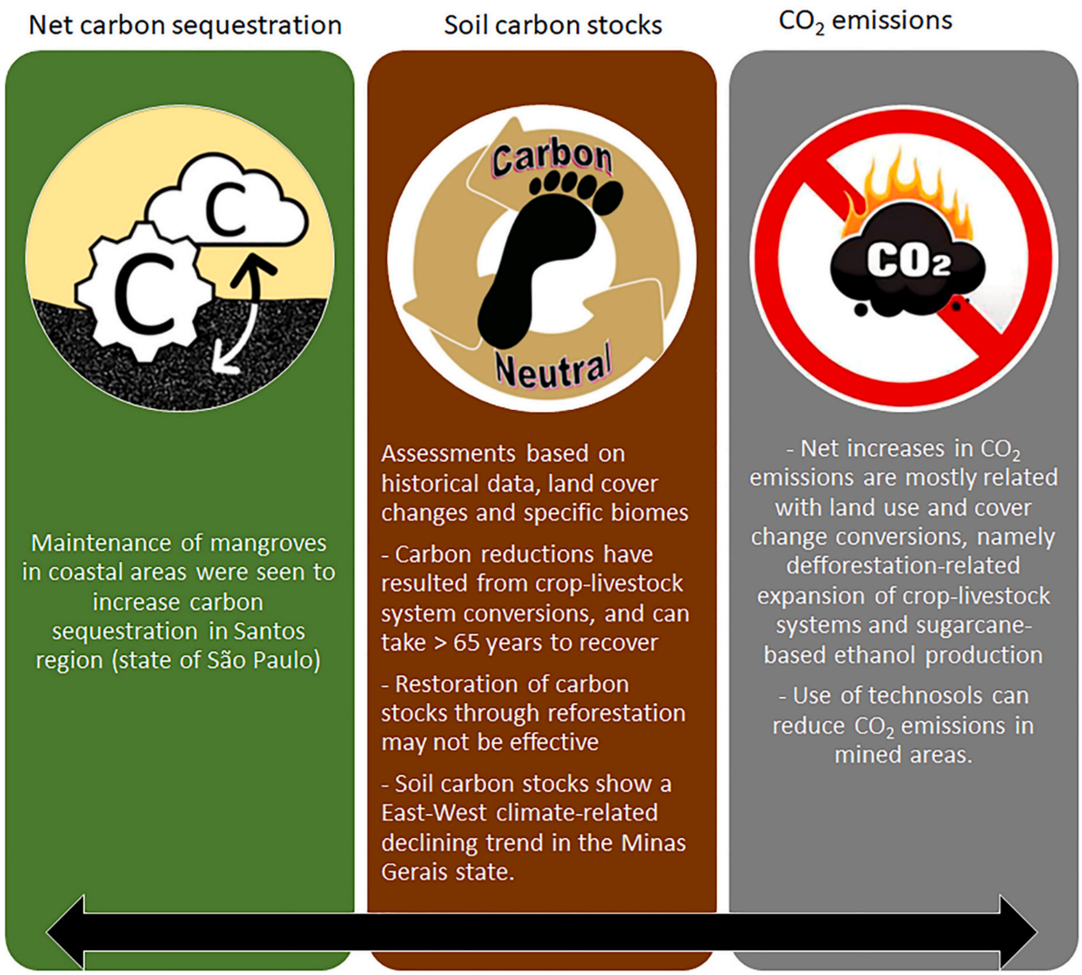

Fig. 6. Key aggregated outcomes of studies addressing carbon soil stocks, net CO_2 emissions and net carbon sequestration.

over the causes of stock variations in the spatial domain. The results indicated an average soil carbon stock of 141.67 t/ha in the 0 – 100 cm layer, with 56% concentrated in the 0 – 40 cm layer. They also outlined an East – West decline across the state expressed in the following sequence (values in t/ha): 256.58 (East) > 174.69 (Central) > 157.84 (South) ≈ 153.15 (North) > 109.87 (West) > 85.94 (Northwest). Besides these two outcomes, significant Pearson's correlation coefficients (r) were found between the carbon stocks per region and the parameters altitude ($r = 0.52$), silt + clay content (0.77), air temperature (–0.53) and annual precipitation (–0.31), meaning that soil carbon stocks were lower in warmer and wetter areas, and higher in fine-textured soils from the highlands. This is an important outcome, because it suggests metrics to assist land use policies related with the carbon agenda.

The emissions of CO_2 occur naturally from the soil, via respiration or microbial-mediated decomposition of residues and organic matter, but the magnitude of those processes depends on various factors, such as the local edaphoclimatic conditions, land use and cover, and soil management. Besides, if the release of CO_2 exceeds assimilation through photosynthesis-mediated generation of soil organic compounds, then there is a net emission and the region becomes a source of greenhouse gases. Otherwise, it is a sink. Land use and cover changes can severely disrupt the balance between emission and assimilation of soil CO_2, in which cases potential environmental consequences develop and can exacerbate if nothing is done to reverse the situation. Usually, nature disturbances are rapidly echoed to scientists that respond with research to understand the on-going changes and propose mitigation or adaptation pathways to decision makers, as have occurred recently in Brazil in the context of CO_2 emissions from crop or livestock systems (Fernandes et al., 2020; Figueiredo et al., 2017; Schaldach et al., 2017), sugarcane-based biofuel production areas (Machado et al., 2017; van der Hilst et al., 2018), and open-pit mined regions (Chaddad et al., 2022; Ruiz et al., 2023). The study of Fernandes and collaborators (Fernandes et al., 2020), for example, analyzed land use and cover changes in the semiarid region of Sergipe state (area: 10,729 km^2) between 1992 and 2017, and forecasted them until 2030 using logistic regression under two forest development scenarios: the "business-as-usual" scenario where the current deforestation trend is to be maintained in the near future; and the "protect forest" scenario that assumes full compliance of future deforestation with the Brazilian Forest code (Federal Law n° 12.651; dated from May 25, 2012). Besides, the authors simulated soil carbon stocks using the Carbon Storage and Sequestration Model embedded in the InVEST suite software (https://naturalcapitalproject.stanford.edu/software/invest), from which net emission or sequestration were deduced. As per the results, important land use and cover changes have occurred in the 1992 – 2017 period related to dry forest declines (from 3,985.91 to 2,395.90 km^2) and increases of cultivated land (from 111.53 to 1,605.98 km^2). Under the "business-as-usual scenario", the dry forests would decrease even further until 2030, to 2,206.22 km^2, and the cultivated land would show a decrease to 1,071.06 km^2; while under the "protect forest scenario" the dry forests would increase to 2,861.23 km^2 and the cultivated land would decrease to 1,213.06 km^2. Considering these outcomes and the changes predicted for all the other land use and cover classes, the results for carbon dynamics was revealed to be net emission under the "business-as-usual" scenario (736,900 t CO_2-eq) and net sequestration under the "protect forest" scenario (481,939 t CO_2-eq). This is definitely a motivation to improve the implementation of

Brazilian's Forest Code, not only in the Sergipe state but across the country as well. The work of Schaldach et al. (2017), called "Carbiocial project", was also based on scenarios but was implemented in areas of tropical rainforest and Cerrado biome vegetation of Pará and Mato Grosso states. The scenarios were set up on the basis of four plausible crop-livestock development pathways anticipated until 2030 and bounded by commodity market constraints (e.g., soybean and meat exports) as well as by different enforcement levels of environmental laws. The scenarios were termed "trend" (the conventional "business-as-usual"), "illegal intensification", "legal intensification" and "sustainable development". They all predicted crop and meat production increases until 2023, but differed as regards the strength of Forest Code enforcement imposed to projected forest to crop-livestock conversions, which increased from the "trend" to the "illegal intensification" then to the "legal intensification" and finally to the "sustainable development" scenario. The predicted land use changes comprised conversions of tropical rainforest + Cerrado vegetation to crop or livestock fields, which spanned the following areas and soil CO_2 emissions: (a) conversions to cropland – "business-as-usual" (area: 29,264 km^2; net emission 56 Mt/y CO_2-eq), "illegal intensification" (94,142 km^2; 150 Mt/t CO_2-eq), "legal intensification" (79,274 km^2; 149 Mt/y CO_2-eq), "sustainable development" (44,845 km^2, 21 Mt/y CO_2-eq). (b) conversions to pastureland – "business-as-usual (152,460 km^2, 326 Mt/y CO_2-eq), "illegal intensification" (75,679 km^2, 196 Mt/y CO_2-eq), "sustainable development" (3 km^2, 0 Mt/y CO_2-eq). As per the simulations, the worst news come from the current trend ("business-as-usual" scenario), because crop-livestock production forecasts will bring additional deforested area amounting to 181,724 km^2 accompanied by net CO_2 emissions of 382 Mt/y CO_2-eq, while the best expectation comes from the "sustainable development" scenario that is based on a deforestation of 44,848 km^2 (75% less) linked to a net CO_2 emission of 21 Mt/y CO_2-eq (94% less). The last case of CO_2 emissions from crop or livestock systems we present in this review refers to the experimental work of Figueiredo et al. (2017). The research covered two 100 × 100 m^2 grazing sites located 3.88 km apart from each other in the vicinity of Mococa city, state of São Paulo. One site was described as degraded *Brachiaria brizantha* pasture, with no maintenance implemented for at least five years, and the other was described as managed pasture, with rotational grazing and application of dolomite and nitrogen fertilizers for three consecutive years. The aim was to compare CO_2 emissions between the two sites and the results indicated emissions of 640.7 kg/ha from the degraded pasture and 440.0 kg/ha in the managed pasture, suggesting the implementation of management practices as strategy to reduce greenhouse gas emissions from pastureland. It is worth recalling that pastures in Brazil occupy more than 150 Mha (data from 2021; https://atlasdaspastagens.ufg.br/map), a large portion of which presents some level of degradation. The soil CO_2 emission from biofuel productive regions was also an important research topic in Brazil in the recent past. For example, the work of Machado et al. (2017) quantified soil CO_2 emissions from an area where sugarcane, corn, beet-sugar, cassava and rice were being used as feedstocks for ethanol production. The study was conducted in the Morretes city located in the state of Parana because of its specific suitability, viz. because it comprised large areas of all crops distributed within a region of similar edaphoclimatic conditions. The results indicated the lowest emissions from sugarcane fields (4.7 t/ha), followed by corn (4.9 t/ha), rice (10.6 t/ha), cassava (14.5 t/ha), and beet-sugar (17 t/ha) fields. The policy implication was that, at least under the edaphoclimatic conditions of Morretes city, sugarcane should keep the status of best option for ethanol production. The study of van der Hilst et al. (2018) also relied on the assumption that sugarcane is indeed the best feedstock for ethanol production, and used a framework model to forecast sugarcane areas and corresponding CO_2 emissions at the scale of Brazil required to meet an increasing ethanol demand until 2030, with and without the implementation of mitigation measures. The model includes the "Magnet", "PLUC" and "Carbon" modules. The "Magnet" module uses population, gross domestic product, sugarcane production and ethanol demand data to project land requirements for sugarcane production into the future. These outputs are used by the "PLUC" module to determine the location and type of conversion necessary to accommodate the requested area, in this case across Brazil. Finally, the "Carbon" module estimates CO_2 emissions from the projected sugarcane areas. In the study of Hilst and collaborators, the framework was repeated for a reference scenario (without implementation of mitigation measures) and a number of scenarios where mitigation measures are implemented in separate or all at once. The measures included improved sugarcane productivity (doubled yields), shift to second-generation ethanol (from bagasse and sugarcane straw or from eucalyptus), and strict conservation policies (no sugarcane expansion at the expense of deforestation). The ethanol production in Brazil was projected to increase from 23.9 to 54.2 × 10^9 L in the 2012 – 2030 period. If no mitigation measures were implemented, then the land requirements for the production of sugarcane would increase from 10.1×10^6 ha to 13.6×10^6 ha, mostly in the states of Mato Grosso do Sul, Goiás and São Paulo, and through cropland (58%), grass and shrubland (19%) and rangeland (14%) conversions. The corresponding carbon loss through CO_2 emissions was projected to be 86 × 10^9 kg C, with a large share from the soil. If, on the other hand, all mitigating measures were put in place, then the required sugarcane area would reduce to 9.1 × 10^6 ha (10% less) whereas the CO_2 emissions would become 54% less than those from the reference scenario. Land use changes related with the net expansion of crop-livestock or biofuel production systems, especially if occurred at the expense of forest declines, are space-wide changes with potential for regional intensification of soil CO_2 emissions. Nevertheless, other more localized changes, such as those related with mining, are also worth of investigation and report considering their probable large effect on the soil CO_2 dynamics of affected areas. In that context, the work of Chaddad et al. (2022) used Landsat satellite images and soil carbon stock datasets to reconstruct the deforestation around the "Salobo" copper mine area located in the municipality of Marabá, state of Pará, and estimated concomitant CO_2 emissions. The mining area expanded from 0.9 ha in 2005 to 2214 ha in 2020, via tropical rainforest deforestation, in the course of which the CO_2 emissions increased from 5000 t to 1.82×10^6 t. Somehow, although unrelated, the work of Ruiz et al. (2023) complements the previous study because it proposed construction of technosols for mine reclamation with the aim to reduce the CO_2 emissions from mining areas. We recall that a technosol layer is thicker than 20 cm within a 100-cm deep profile, and comprises more than 20 % artifacts containing more than 35% rubble and refuses of human habitation. The authors detected 5.4 Mha of mining areas spread across Brazil, from which they estimated potential CO_2 emissions of 1.68 Gt CO_2-eq, mostly from the tropical climate regions (1.05 Gt CO_2-eq) and much less from the semiarid climate regions (0.04 Gt CO_2-eq). They also estimated soil stock recoveries (and hence CO_2 sequestration) in the 31 – 60% range, if technosols were used in the reclamation of those mines through the refilling of excavated areas with those materials.

Sequestration of CO_2 in longstanding pools of organic (e.g., forest biomass) or inorganic carbon (e.g., carbonate rocks) is likely the best strategy to balance CO_2 emissions and slow down (even reverse) the ongoing warming of planet Earth. In that regard, studies on CO_2 sequestration are as necessary, and one dedicated to Brazil is reported in the present review (Rosa et al., 2022). In that study, the Atlantic Forest Collection 4.1 (1985–2018) of MapBiomas project (https://brasil.mapbiomas.org/en/project) was used to extract areas of mangrove forests located in the coast of Santos and São Vicente cities (state of São Paulo). Mangroves are important sinks of carbon dioxide but were threatened in the studied region because of uncontrolled urban, industrial and maritime port expansion. For example, in Santos the protected mangrove forests represent nearly 20 – 25 % of all mangrove area (155 km^2) and among the protected forests nearly 90% are illegally occupied with suspended dwellings built by poor families. Notwithstanding these threats, the authors detected an increase in the protected mangrove area, from 3,375 ha in 1988 to 3,764 ha in 2018, and estimated corresponding increases of carbon stocks (29% in Santos and 14% in São Vicente). Using the InVEST Coastal Blue Carbon model, the net CO_2 sequestration was also estimated, namely 925,393 t CO_2-eq in Santos and 287,130 t CO_2-eq in São Vicente, considering the entire studied period.

4.4. Conservation of soil through sustainable agriculture, grazing and biofuel production

Sustainable landscapes are the utopia of a longstanding equilibrium and symbiosis between natural processes and anthropogenic occupation of territories, and can effectively occur in remote regions from planet Earth working as legacy of human-nature integration for future generations (Franco-Moraes et al., 2019). However, utopias likely deviate from reality when economic growth is unbalanced with nature conservation, in which case the human pressure on the natural system tend to exacerbate as occurs in the most developed states of Brazil (Bezerra et al., 2022). Signs of imbalance are the inadequate uses of soil and the consequences derived therefrom, which were described in the former sections as amplified soil erosion (and ultimately land degradation), soil contamination, and generation of greenhouse gas source areas. These inequities and their penalties can be contained or even reversed with a cost, which includes shifting the agribusiness, livestock and biofuel energy sectors towards sustainable production systems. Subsides from science have been granted to Brazilian actors in that regard, as per the large number of publications found in the literature from the recent past. Key contributions are reported in the forthcoming discourse, the outcomes of which are portrayed in Fig. 7.

The trends of recent research on sustainable production systems mostly seek ways to prevent soil from physical or chemical degradation, as well as pathways to intensify production (produce more in the same or less space) or to expand productive areas with environmentally supported rules. In general, the studies start with the modeling of land use changes overtime followed by the interpretation of their patterns (Souza et al., 2022), to understand the current production system. As regards agriculture, various publications have thought about these matters and proposed methods to accomplish sustainable production (Cabral, 2021; de Amorim Júnior et al., 2022; Lucas et al., 2023; Martini et al., 2015; Medeiros et al., 2021; Ofstehage and Nehring, 2021). A pathway to sustainable production of crop systems relies on the combat of soil erosion. This can be done through implementation of no-tillage agriculture, because crop residues are left on place after the harvest, protecting the surface from raindrop impacts and subsequent runoff and soil loss. The work of Ofstehage and Nehring (2021) presented a comprehensive analysis of pros and cons of no-tillage agriculture practiced across the Brazilian's Cerrado, which was the starter biome where this technique has been applied in the country because of its flat to undulated topography that favors mechanization. Irrespective of recognized benefits for soil conservation and health, no-tillage agriculture has the financial constraint of requiring specific planters capable of working through cover crops, and the necessity to control weeds through more intense herbicide dressings because, conversely to tilled agriculture, the no-tillage method does not bury weeds and other unwanted pests through overturning the soil's top layer. In addition, when practiced in the Cerrado, productivity is very much dependent on the use of hybrid seeds adapted to soil acidity. Nevertheless, Brazil has experienced a sharp increase in the implementation of no-tillage agriculture from a residual coverage in 1990 to more than 25 Mha in 2005. The control of weeds is not restricted to no-tillage agriculture and is key to conserve soil health and crop productivity. Weed management has been extensively investigated in the work of Oliveira et al. (2021), which covered 5.7 Mha of crop and livestock productive areas spread across the entire territory of Brazil. The study comprised a survey that involved 343 stakeholders from 21 states, among agronomists (69%), university and industry representatives (22%), growers and consultants (9%). The profile of cropping systems included tilled and no-tilled areas, one to three years of successional crops, irrigated and non-irrigated crops, and crop *versus* crop-livestock systems. The interviewed stakeholders reported horseweed, sourgrass, morningglory, goosegrass and dayflower as the prevalent weeds because of their resistance to glyphosate. In general, the problem was overcome with the use of other herbicides or adoption of alternative methods, such as crop rotation/succession (75% of cases) or cover crops (61%), among others. In addition to weed control, soil fertility requires the replenishment of nutrients with fertilizers to compensate the amount removed with the harvest. Conventional fertilizing, with organic and inorganic products, is a common place and the most used technique in crop and crop-livestock systems, and works well if properly managed. However, under the auspices of

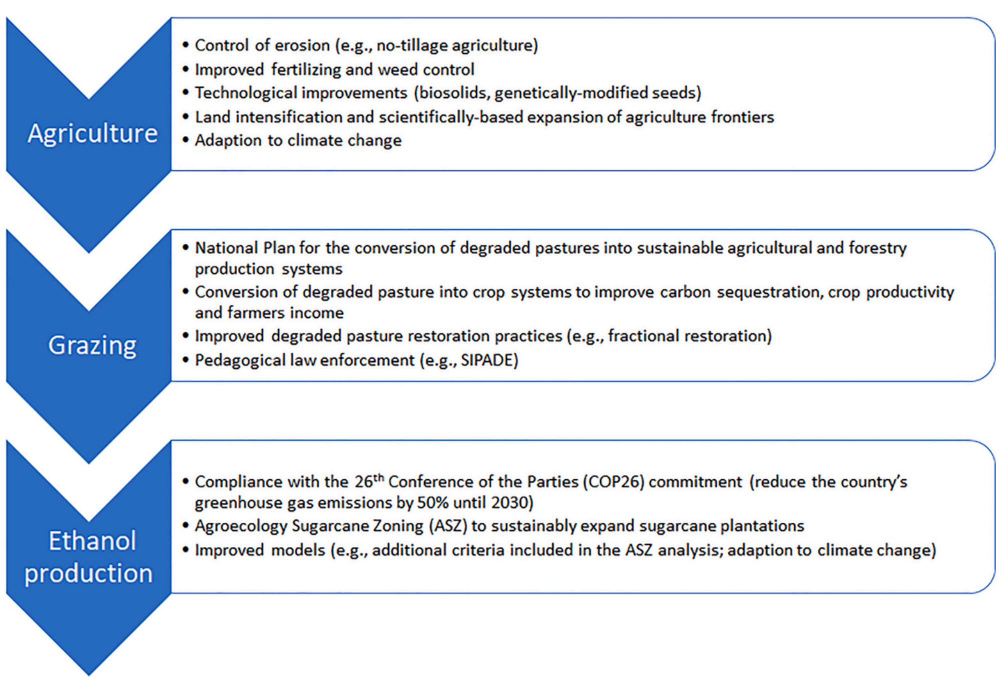

Fig. 7. Key aggregated outcomes of studies addressing pathways towards sustainable production systems (agriculture, grazing, ethanol production).

circular economy, global sustainability, and reduction of production costs, biosolids can complement conventional fertilizers. They are a by-product of sewage treatment and their reuse in agriculture can reduce the volume sent to landfills, with benefits to the environment. They contain recyclable nutrients and hence are generally harmless to the soil, unless they also contain other elements in detrimental concentrations, such as pathogens or heavy metals. The study of de Amorim Júnior et al. (2022) investigated biosolids produced from treated sewage in the Imbirussu Wastewater Treatment Plant, located in the city of Campo Grande, the capital of Mato Grosso do Sul state. These biosolids presented high agronomic potential (comparable to other wastewater treatment plants in Brazil), because of their high nutrient concentrations per ton of treated sewage (33.64 ± 6.08 kg/ton of nitrogen, 20.55 ± 3 kg/ton of phosphorus and 1.16 ± 1.11 kg/ton of potassium), namely much higher than those in cattle manure, for example (3.45 ± 1 kg/ton of nitrogen, 1.18 ± 0.2 kg/ton of phosphorus and 3.25 ± 2.5 kg/ton of potassium; as per references used by do Amorim Júnior and collaborators in their study). As regards pathogens (e.g., *Escherichia coli*), the study concluded that the biosolids produced in the Imbirussu plant can be recycled in forest plantations and recovery of soils and degraded areas, but not in soils used to grow food products consumed raw, in keeping with the CONAMA's Resolution 498/20. However, no restrictions were set relative to heavy metal concentrations.

A major challenge posed to sustainable agriculture stems from population growth that demands more food and likely more land to produce it. The sustainability problem can be overcome with intensification, meaning produce more in the same or even less space through technologic or other improvements. Sustainable intensification can be real if accomplished with no additional environmental impacts, or via scientifically supported and environmentally reasonable expansion of agriculture frontiers. A paradigmatic case of large-scale agriculture expansion was the reclamation of Cerrado biome lands for production of soybeans (mostly) since the 1970s, a native vegetation to agriculture conversion that became known as the "Tropical Revolution" or "Brazil's Green Revolution". This case was nicely documented in the work of Cabral (2021), in line with the commemoration of Embrapa's 40th anniversary in 2014, recalling that Embrapa – Empresa Brasileira de Pesquisa Agropecuária is the Brazilian's company for agronomic research (https://www.embrapa.br/en/international). The so-called revolution hinges on the development of new cultivars that allowed farming in the acid and previously useless soils under Cerrado vegetation. Despite the achievement, the Cerrado to agriculture conversions were not exempt from many disputes, namely as regards the detrimental impact of soybean specialization and agrochemical intensification, land grabbing and wealth concentration, biodiversity loss, among others. Other examples from Brazil, which addressed expansion of agricultural land including biodiversity loss issues were published by Lucas et al. (2023) and Martini et al. (2015). The study of Martini and collaborators was conducted in the so-called Legal Amazon (4,217,247.56 km^2), which spans vast areas of Acre, Amapá, Amazonas, Pará, Roraima, Rondônia, Mato Grosso, Maranhão and Tocantins states. Using data from the Terra Class mapping project (http://www.obt.inpe.br/OBT/assuntos/projetos/terraclass), the authors delineated potentially available areas (PAA) for expansion of agriculture from secondary vegetation and degraded pastures, meaning non-native forests. However, before becoming PAA the polygons derived from that delineation were subject to exclusion of public lands or parcels protected by the Brazilian's Forest Code (Federal Law n° 12.651; dated from May 25, 2012) such as legal reserves located inside private lands and areas of permanent preservation spread along water courses. After this exclusion, the polygons underwent further screening as to extract just the parcels that intersected regions of medium to high fertility soils and low slope terrains (< 13%). The results indicated a total of 200,357.06 km^2 of PAA in the Legal Amazon free of any legal restriction and with favorable potential for agriculture, meaning 4.75%. The contributing states were mostly Pará (93,749.94 km^2, 2.22%), Mato Grosso (34,635.86 km^2, 0.82%), Rondônia (22,961.10 km^2, 0.54%), Maranhão (21,932.92 km^2, 0.52%) and Amazonas (12,699.98 km2, 0.30%). Finally, the study of Lucas and coworkers highlighted biodiversity damages caused by land use conversions to agriculture. The work was developed at national scale and resorted to the life cycle assessment (LCA) method. It covered various commodities produced in Brazil (e.g., sugarcane, coffee, oranges or corn) screened through ecoregion (biome), all six included (Cerrado, Atlantic Forest, Pantanal, Caatinga, Pampas and Amazon). Firstly, the LCA determined the evolution of functional units (FU; the area required to produce one kilogram of crop) in the recent past (2015 – 2020 period), using data from the Brazilian Institute of Geography and Statistics (https://www.ibge.gov.br/), and projected the patterns into the near future (until 2035). Secondly, biodiversity losses (mammals, birds, amphibians, reptiles and plants) related with the aforementioned projections were anticipated in the six ecoregions. The study reported general declines of functional units, with corresponding biodiversity gains. There were, however, cases where the FUs were anticipated to increase with negative consequences for biodiversity (decline). They refer to maize in the Atlantic Forest, orange in the Caatinga, maize and sugarcane in the Pampas, maize and orange in the Pantanal. Notwithstanding the report of biodiversity gains, the study authors proposed the implementation of technologic developments to improve even further the positive results and resolve or at least mitigate the negative ones. The suggestions included the practice of integrative grain, livestock and timber production, meaning all goods produced in the same place. This so-called ILPF approach encompassed 11.5 Mha in 2016, spread across the southeast, south and central-west regions of Brazil, and are thought to enhance productivity and better use of resources.

Sustainable cattle ranching is a major challenge in Brazil because degraded pastures represent a large share among the area used for livestock production (150 Mha, data from 2021, https,//atlas-daspastagens.ufg.br/map). Recently, the Presidential Decree no. 11,815, dated of December 5, 2023, launched the National Plan for the conversion of degraded pastures into sustainable agricultural and forestry production systems. This is a major landmark, which is expected to leverage future legal and policy initiatives capable of bringing the agrosilvopastoral business into a new more environmentally friendly era. In fact, some important initiatives already started implementation, such as the SIPADE – Sistema para Apoio no Diagnóstico de Pastagens Degradadas (http://sipade.com.br/assets/static/home/index.html) in the state of Minas Gerais. This is a program to pedagogically enforce the restoration of degraded pastures. It embeds a software used by military policy officers to identify levels of pasture degradation in the field, and determine legal action where severely degraded pastures are confirmed. As for agriculture, scientific research on sustainable livestock production has also contributed with knowledge to subsidize decision-making. In this review, a few examples are quoted to document significant contributions (de Oliveira Silva et al., 2017; Kruger et al., 2022; Rufin et al., 2015; Silva et al., 2017a). A research line of paramount importance refers to intensification of grazing, in this case meaning producing more in the same area, with more profit and less environmental impact (e.g., net carbon sequestration). Given its importance, intensification of livestock production is worth of a detailed contextualization, and two cases will be discussed in the sequel (Rufin et al., 2015; Silva et al., 2017b). The work of Silva et al. (2017b) was developed in a 600 ha farm located in the city of Campo Grande, the capital of Mato do Grosso do Sul, using a model for planning grazing beef production in the long term. The model tested three restoration practices and evaluated their performances as regards productivity, net production value and carbon dynamics in a life cycle of 20 years. The restoration practices were all based on liming, fertilizing and incorporation of organic matter in the soil, but differed in the dynamics of restoration, as follows: (1) Traditional Restoration Practice (TRP), where restoration occurs in cycles separated 8 to 10 years from each other. In this case, soil organic matter oscillates between 5 and 20 t/(ha·yr), being maximum when restoration is done in the beginning of each cycle and minimum at the end of the same cycle; (2) Uniform Restoration Practice (URP), where restoration to a better productivity level is applied several times to the entire farm within the 8 to 10 years period. In this case, the contents of organic matter in the soil also oscillate, but within a narrower band (15 to 20 t/(ha·yr)); (3) Fractional Restoration Practice (FRP), where parcels within the farm are restored to better productivity levels, which can differ among parcels. In this case, the organic matter contents in the soil show a somewhat sinusoidal pattern oscillating between 17 and 19 t/(ha·yr). For all scenarios, the boundary conditions were: the farming was based on retained capital or access to the ABC credit line; the initial stage of pasture productivity went from low to high; the cattle diet was based exclusively on forage from pasture *Brachiaria*. The results pointed to TRP beef productivities in the range 96 – 104.7 kg CWE/(ha·yr) (without the ABC credit line) and 167.6 kg CWE/(ha·yr) (with ABC), depending on the initial stage of pasture productivity, where CWE means carcass weight equivalent. The corresponding net production values ranged from negative (−67 R$/(ha·yr)) to positive (53.5 R$/(ha·yr)), forecasting the unprofitability of low productivities. On the other hand, as regards carbon dynamics the TRP showed gains and losses of CO_2, but represented a net sink in the 20-year period because soil organic carbon increased from 45.2 to 47.2 t/ha in that timeframe. The URP and FRP performed better in all aspects: the minimum productivity could go from 96 to 207.4 (URP) or 213.4 (FRP) kg CWE/(ha·yr), with positive net productive values around 270 R$/(ha·yr); the soil organic carbon increased from 45.2 to 60.5 t/ha. The sustainable increase of cattle ranching intensity has reflexes on deforestation, because the increasing productivities accompanied with a more profitable business reduce the need to expand pastureland. Thus, the analysis of land use trajectories can be used to monitor cattle ranching intensity. The study of Rufin et al. (2015) did that in the Novo Progresso municipality located in the state of Pará, using Landsat images from the 1984 – 2012 period. The results revealed the period to set on a pasture area, which ranged from 4 to 10 years. Within the established area, the removal of woody vegetation decreased from grazing areas set on the 80s and 90s, relative to those set from the year of 2000 onwards, pointing to intensification. The identified causes of intensification after 2000 were penalties to ranchers who cleared their land from woody vegetation in excess of 20%, the eradication of the foot and mouth disease, which unlocked the international beef market for the region, changes in the patterns of temperature and precipitation, among others.

Brazil has the ambitious commitment to reduce the country's greenhouse gas emissions by 50% until 2030, since its formalization in the 26th Conference of the Parties (COP26) held in Glasgow (United Kingdom) in 2022. Production of biofuels may contribute to accomplish this goal because they can partly replace the use of fossil fuels in the economy, the combustion of which is a major source of greenhouse gas emissions worldwide, unlike biofuels such as ethanol. Thus, talking about greenhouse gas emissions in Brazil is intimately related with speaking about sugarcane production, which is the main feedstock of biofuels in the country. Brazil is the World largest producer of ethanol from sugarcane, the production of which grew exponentially from 2001 onwards, going from nearly 10^9 L/yr in that year to approximately 32^9 L/yr in 2022 (https://www.gov.br/mda/pt-br/). The question in using sugarcane to feed the ethanol energy sector in Brazil relies on how land for sugarcane production will be planned in the long term to sustain this growing demand, namely how can sugarcane fields expand from conversion of other uses, under the backdrop of sustainable production. To subsidize decision makers with updated scientific evidences, academic studies have investigated recently the sugarcane sector from the perspective of potentially available areas. A couple of examples we bring here used the so-called Agroecology Sugarcane Zoning (ASZ) approach to handle the problem (Granco et al., 2019; Turetta et al., 2017), which is a technical instrument used to guide sugarcane cultivation in Brazil, legally enforced through the Decree no. 6.961, dated from September 17, 2009, replaced by the Decree no. 10.084 dated from November 5, 2019. According to Turetta and collaborators (Turetta et al., 2017), the ASZ unequivocally guides practitioners through the identification and mapping of areas with potential for sugarcane cultivation based on biophysical parameters such as soil type or climate, but lacks a comprehensive assessment because economic and social dimensions have been excluded from the analysis. To overcome this setback, the authors proposed an improved framework where the potential to use land for sugarcane cultivation at the country scale is built upon three pillars: (1) the environmental pillar – only favorable areas are included, as indicated by the ASZ; only hillsides with slope < 12% are included; areas without native vegetation are considered; areas that are not for food production are considered; Pantanal and Amazon biome lands are excluded; (2) the economic pillar – expansion of sugarcane in a region must create employment opportunities and generate income especially for small farmers; speculative land prices must be controlled to allow increased participation of low-income property owners in the agribusiness; land competition must be regulated and monitored, to balance the use of all resources it contains or can generate, including energy production from sugarcane; (3) the social pillar – sustainable production must rely on fair salaries and labor conditions granted to farm workers by the employers. In the work of Granco et al. (2019), the authors investigated the impact of climate change on the area officially set potential for sugarcane production in Brazil based on the ASZ method, which is 63 Mha. In 2022, the area used in the country for production of this crop was 8.3Mha. This is far from the potentially available area, but the authors questioned if climate change will not mismatch the ASZ threshold of 63Mha with the real suitability projected for different climate parameters such as precipitation and temperature. Thus, they used an ensemble of global climate models (17 in total) under representative concentration pathways (4.5 and 8.5) to anticipate conditions for sugarcane cultivation by 2050, namely as regards the aforementioned parameters. The results were clear about the potential for a drastic decline of areas with climatic conditions appropriate for sugarcane production by that time. The ensemble models predicted just 1.5 Mha of these areas inside the ASZ area, which represent a 97.5% decrease when checked against the 63Mha. Even if parcels located outside the ASZ were added to this number because of their suitability determined by the ensemble model, the total area would raise to no more than 7 Mha. This is alarming! The main reasons pointed by Granco et al. (2019) for this catastrophic outcome were the low temperatures projected for the four driest months of Brazilian's tropical climate (June – September), because they promote soil frost hindering sugarcane development. Besides, a drier climate also projected by the ensemble model may increase areas requesting irrigation, which is a criterion used to exclude an area from the ASZ map. The authors proposed measures to mitigate these probable declines, which comprised the replacement of current sugarcane varieties with others genetically modified to resist and perform well under future climate conditions, but highlighted some reserves related with development costs and bureaucratic delays. The works of Granco et al. (2019) and Turetta et al. (2017) were both based on the ASZ method and developed at the country scale. But other studies, spatially more restricted and(or) based on different methodologies, are also worth referencing. For example, the study of Martini et al. (2018) used a Boolean inference technique to identify areas potentially available for sugarcane production in the state of São Paulo. The study used the year of 2005 as reference and identified 4,875,490 ha of those areas (19.6% of São Paulo state area). The authors quantified the sources from which the sugarcane business could reclaim land, and found 80.9% available through conversion of pastures, 14.5% through conversions of semi-perennial crops and 4.6% through conversions of other uses. In addition, they identified 2,777,147 ha (79.3%) with high potential because of their proximity (≤ 25 km) to ethanol mills. The study of Ferreira Filho and Horridge (2014), on the other hand, used a dynamic general equilibrium model calibrated with data from the Brazilian's Agrarian Census (https://www.ibge.gov.br) to diagnose indirect effects on land use change resulting from ethanol production expansion in the country, using the 2006 – 2020 period as reference. The study covered

15 regions with a mix of agrosilvopastoral activities and the ultimate goal was to determine how much area needs to be reclaimed from a specific use (e.g., pasture) as to produce one hectare of sugarcane. In order to get an answer to this working question, the authors fed the model with data on the dynamics of agricultural markets spanning the research period, as well as the corresponding land use transformation matrix. They also applied boundary conditions to the model, namely prohibited land use conversions and respective areas (e.g., agriculture frontier) The output was that a hectare of sugarcane needs a conversion of 0.14 hectares coming from another use. A final example brought into the current review alerts for environmental impact assessment issues related with the sugarcane supply chain, which were summarized by Gallardo and Bond (2011) for the state of São Paulo. This state was selected for the study because of its major share in the production of sugarcane and ethanol in Brazil (nearly 60%). The authors reviewed 32 Environmental Impact and Preliminary Environmental Impact Assessment reports produced under the licensing of sugarcane enterprises (under the terms of CONAMA's Resolution no. 1, dated of January 23, 1986) and concluded about deficiencies in the assessments made, because topics such as labor conditions and social responsibility, water resources and residues were just partially addressed and, even worse, greenhouse gas emissions and food security were not addressed at all. A review of Environmental Impact Assessment protocols is therefore needed, if not done since the Gallardo and Bond's study.

4.5. Soil and land use policies

This section relates with policy views over topics discussed before. In that context, the forthcoming paragraphs will review publications that were interested in soil conservation (Klingen et al., 2012; Polidoro et al., 2021; Rittl et al., 2015; Stuchi et al., 2021; Zolin et al., 2014), integrated production systems (Cortner et al., 2019; de Souza Filho et al., 2021; Loch et al., 2021) and land use transitions (Costa Coutinho et al., 2017; Oberling et al., 2013; Silva et al., 2017b). The key aggregated outcomes are portrayed in Fig. 8.

The study of Stuchi et al. (2021) reviewed seven federal public policies for the conservation of soil and water in Brazil and searched common points among them to support the participatory construction of a new "National Plan for Soil and Water Sustainable Management" (NPSWSM). The policies were: National Environment Policy (PNMA), National Water Resources Policy (PNRH), Law on the Protection of Native Vegetation (Forest Code), National Policy on Agroecology and Organic Production (PNAPO), National Policy on Climate Change (PNMC), National Policy for the Recovery of Native Vegetation (PROVEG), and National Policy to Fight Desertification and Mitigate Drought Effects (PNCDMES). The search for common points comprised six topics: legislation, integration, planning, conservation, recovery, and monitoring. The idea was to look into the strategies and tools used by the various policies to handle these topics, identify congruences and design an integrative discourse capable of being used as basis for the aforementioned NPSWSM. The authors indeed noted complementarity among the policies and, more importantly, strong points in all of them. For example, the PNMA, PROVEG and Forest Code already have regionalized frameworks, either legal or institutional, which can be adopted by the National Plan, while the PNRH is strong in participatory water governance because the action of river basin committees involves a multiplicity of private and public actors for 30 years. Thus, Stuchi et al. (2021) proposed a NPSWSM built upon these complementary views and strong points considering the synergic effects they could bring into the new policy. Another view over soil conservation policies was presented in the study of Polidoro et al. (2021). In their work, the authors highlighted the need to amplify and intensify the implementation of existing public policies and plans based on conservation agriculture (e.g., the ABC+ plan), either through zero-tillage (ZT) or integrated crop-livestock-forest (ICLF) systems, because of their role in soil erosion prevention and on the huge positive economic impacts derived therefrom (in 2020, they were estimated 1.5 billion US$ for ZT and in 0.5 billion US$ for ICLF). In that regard, the authors recalled how the PronaSolos project will provide soil data with better quality at the National level to improve the application of ZT and ICLF, and how the updated National Soil and Water Conservation Program will increase the use of conservation technologies and practices. The study of Klingen et al. (2012) narrowed the policy scope to the farmer's view of agroecological *versus* conventional agriculture. In brief, the authors wanted to test if these land management practices, namely their adoption by farmers, was related with the farmers' knowledge about soils. The field work was conducted in the Araponga area, state of Minas Gerais, and involved 24 smallholder farmers with contrasting management practices, 10 agroecological and 14 conventional. The working hypothesis resulted false because the two groups of farmers revealed similar and extensive knowledge on soils. Thus, the reasons for adopting agroecological or conventional management practices should originate from elsewhere. The authors encountered reasons on the farmers' knowledge about the biophysical environment, on individual choices and motivations, on feedbacks to external factors, among others. Within these contexts, Klingen et al. (2012) established profiles for the two groups that can be

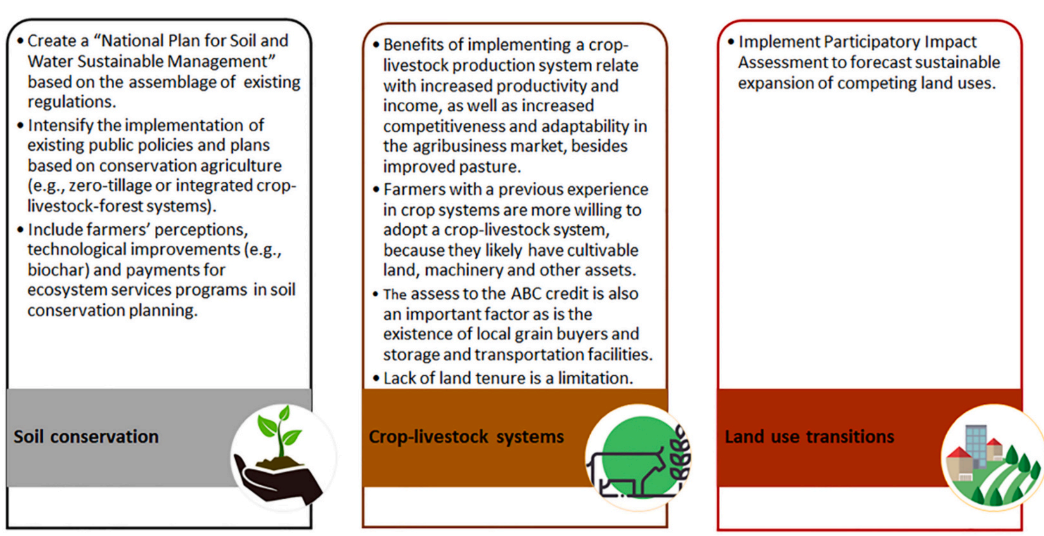

Fig. 8. Key aggregated outcomes of studies addressing perceptions on the efficacy of land use policies relative to soil conservation, crop-livestock production systems, transitions of competing land uses.

used in future municipal or regional smallholder farmland management plans. The agroecological farmers use cattle manure, compost and other organic fertilizers, practice agroforestry with multiple crops included, are members of cooperatives and are willing to recover week soils. The conventional farmers, on the other hand, use commercial fertilizers and lime and see this practice as sole pathway to improve soil quality, tend to produce a single crop with no integration of forestry, and do not belong any organization. Studies tackling specific soil conservation policies were reported in the works of Rittl et al. (2015) and Zolin et al. (2014). For example, the biochar agenda was discussed from the Policy Arrangement Approach in the study of Rittl et al. (2015). In that context, the authors showed how key actors (e.g., the Embrapa, the Museu Paraense Emílio Goeldi), discourse (climate change mitigation, improving crop residue management, or improving soil fertility), power (strategic coalitions) and rules (e.g., legislation, measures) evolved overtime. Using the tools of social network analysis, the authors revealed that the biochar debate has been mostly driven by science experts and much less by farmers or farming companies, policy-makers, or other actors. Besides, among experts, those from Embrapa research company occupy leading positions, and the discourse evolved from the climate change mitigation to improving soil fertility once the actors understood that biochar produced from crop residue could have a major role in that regard. However, the biochar discourse focused on the carbon market is emerging and gaining influence at the National scale. The study of Zolin et al. (2014), on the other hand, was the first municipal initiative to use a Payments for Ecosystem Services (PES) scheme in the soil conservation cause. The study was conducted in the Posses River basin located in the municipality of Extrema, state of Minas Gerais, and used the Universal Soil Loss Equation to estimate the effect on soil loss resulting from the implementation of a PES program in the region, called "Conservador das Águas". The research reported a substantial decline of soil erosion, with losses dropping from 30.63 t/(ha·yr) in the period before the program to 7.06 t/(ha·yr) afterwards.

The shifting of monocultures or livestock grazing into integrated production systems have also been investigated from the policy stand point, with the support of scientific evidences. In the present review, we highlight recent research conducted at farmers' perception scale. The study of de Souza Filho et al. (2021) used the responses of 175 farmers from 30 municipalities of São Paulo state, to shed light over factors that limit the conversion of cattle ranching to crop-livestock systems or to livestock-forestry systems. The data were treated with multinomial logit models, which indicated various factors. The assess of cattle ranchers to potentially cultivable land and capital for crop production were major factors, complemented with the knowledge on crop farming. In that regard, farmers with a previous experience in crop systems were more willing to adopt a crop-livestock system, because they likely had cultivable land, machinery and other assets. The assess to the ABC credit was also an important factor as was the existence of local grain buyers and storage and transportation facilities. In the absence of this grain trading infrastructure, the ranchers were keener to adopt livestock-forestry rather than crop-livestock systems. The study of Cortner et al. (2019) also reviewed farmers perceptions on the suitability of intensifying production systems through the crop-livestock model, but were interested in the Brazilian Amazon. Here, the agricultural land area is mostly occupied with low-income and low productivity ranches with a vast share of degraded pastureland. Thus, agriculture intensification could be a promising strategy to improve the farmers welfare. The study involved 33 interviews to people who had their farming activities located in the Acre, Mato Grosso, Pará and Rondônia states. Among the sample, 18 cases represented adopters and 15 to non-adopters of crop-livestock farming. The interview results revealed perceived benefits of implementing a crop-livestock production system related with increased productivity and income, as well as increased competitiveness and adaptability in the agribusiness market, besides improved pasture. The barriers were mostly economic, related with high upfront costs, limited access to credit and uncertain profitability compared to alternative sources of income, but also structural related with poor infrastructure, difficulty to obtain qualified labor, and unfavorable regulatory environment. Finally, the desired policy changes were mostly centered on improved transportation and supply chain infrastructure, technical assistance and support for agricultural labor training, expedited loans and payments for ecosystem services to adopters of integrated crop-livestock systems, and improved land tenure. The study of Loch et al. (2021) discussed the determinants of an agroecological transition experienced by farmers from 8 agrovilas located in the municipality of Alcântara, state of Maranhão. The transition aimed to change the landscape from monocrop cultures where the system's resilience was based on the slag-and-burn method that temporarily makes the soil fertile and eliminates weeds and pests, to agroforestry systems based on crops and fruit trees where resilience is based on improved biodiversity that also improves the soil fertility and keeps the unwanted weeds and pests away, but keeps those conditions in the long term. The transition project lasted from 2014 and 2017 and was framed in a partnership set up between local community members and researchers from the State University of Maranhão, Agroecology Graduate Program. The enterprise was financed by public agencies and involved, among other initiatives, training through courses and workshops, implementation of sustainable productive systems and continued technical assistance. The farmers who participated in the project noticed benefits from the transition, namely weed decline, but claimed for policies capable of improving land tenure security as measure to increase the number of adherents.

Land use transitions were the last research line included in the present review of policy approaches to land and soil issues, supported with scientific data and models. The reviewed studies discussed determinants of forest regeneration in the Paraíba valley located in the state of São Paulo (Silva et al., 2017b), the Strategic Environmental Assessment of plans to expand silviculture of eucalyptus and biofuels in the state of Bahia (Oberling et al., 2013), and the Participatory Impact Assessment to forecast sustainable expansion of sugarcane in the Goiás state. In the first case, depopulation of rural areas pushed by urbanization coupled with land abandonment caused by the aging and decapitalization of rural population, were considered by interviewed experts the main triggers of forest regeneration in the Paraíba valley. Other reasons were the banning of fire use in pasture management practices, the improvement of forest landscapes for tourism, and payments for ecosystem services programs. The second and third cases highlighted the need to involve all economic sectors in the planning of land use to ensure harmonious development within the studied regions.

5. Conclusions

The current review of 77 papers dated from the 2010 – 2023 period highlighted important research trends in the field of soil conservation and its link to ongoing policy and governance initiatives in Brazil. The trends comprised five broad topics: (1) soil properties, geology and land use nexus; (2) soil degradation; (3) soil carbon stocks, sequestration and emissions and promoting drivers; (4) conservation of soil through sustainable agriculture, grazing and biofuel production; and (5) soil conservation policies.

The research on soil properties, geology and land use nexus (17 studies) was mostly focused on geochemical fingerprinting or digital soil mapping studies. In that regard, some studies aimed to determine quality reference values for the monitoring of soil contamination by metals, or delineate geochemically-based rotation maps or adequate yield environment maps to improve crop productivity. Other studies revealed how soil properties influenced aboveground biomass density and diversity in the Cerrado and Amazon biomes, as well as the spatial distribution of forest to agriculture transitions across the country in the long-term; or used soil data to build environmental vulnerability maps and identify areas where the current land use is outside soil capacity; or developed ecological restoration projects based on the spatial distribution of soil quality indicators. Besides these scientific outcomes, a landmark initiative concerning soil in all dimensions was acknowledged in the current review, because of its strategic importance for land management in Brazil. That was the PronaSolos – Programa Nacional de Levantamento e Interpretação de Solos do Brasil, recently launched. This is a long-term project that will gather for the next thirty years many partnership institutions with the purpose of mapping soils and interpreting soil data across the country, with the detail of 1:25,000 and 1:100,000 scales.

Soil degradation was assessed in 19 studies that dedicated efforts to map land degradation, delineated from areas of exposed soil assessed in satellite images or from soil data-based indices. The studies also quantified soil losses and related the results with scenarios of land use or cover changes at the same time that compared them with soil tolerances, nutrient losses, or sediment delivery and siltation problems in reservoirs. A last group of studies on soil degradation provided new insights about geogenic contamination by metals or rare earth elements, or about anthropogenic contamination with arsenic via fertilizing. They also showed how contamination propagates in the watershed through sediment delivery, and checked soil contaminant concentrations against legal thresholds in specific environments such as dump sites or public areas in the urban context.

The review of soil carbon stocks, coupled with CO_2 sequestration or emission, was the subject of 12 studies. In brief, these studies showed how the maintenance of mangroves increased carbon sequestration in the Santos region (state of São Paulo), how the conversion of forests into crop-livestock systems or areas of sugarcane-based ethanol production have reduced the soil carbon stocks and increased the net CO_2 emissions, how long ($>$ 65 years) and ineffective can be the recovery of carbon stocks through reforestation, and how the use of technosols can reduce the CO_2 emissions in mined areas.

The conservation of soil through sustainable agriculture, grazing and biofuel production was addressed in 18 studies within this review. The outcomes related to sustainable agriculture highlighted recent developments on soil erosion control through no-tillage agriculture, improved fertilizing and weed control, technological improvements related to the use of biosolids and genetically-modified seeds, scientifically-based land intensification and expansion of agriculture frontiers, and adaption to climate change. As regards sustainable grazing, the key outcomes emphasized the potential benefits of implementing the recent National Plan for the conversion of degraded pastures into sustainable agricultural and forestry production systems, namely how that conversion can improve carbon sequestration, crop productivity and the farmers' income. Other important results were related with improved degraded pasture restoration practices like fractional restoration, or with pedagogical law enforcement as implemented through the SIPADE program, which embeds a software used by military policy officers to identify levels of pasture degradation in the field and determine legal action where severely degraded pastures are confirmed. Finally, the main results of studies focused on sustainable biofuel production alerted for the country's need of compliance with the 26th Conference of the Parties (COP26) commitment (i.e., reduce the greenhouse gas emissions by 50% until 2030), reported Agroecology Sugarcane Zoning (ASZ) to sustainably expand sugarcane plantations, or presented improved ASZ models via inclusion of additional criteria or adaption to climate change.

The last research topic included in this review was about soil and land use policies and comprised 11 studies. In general, these studies were strong in recommendations about sustainable soil conservation, crop-livestock systems and land use transitions. In the first case, the studies proposed creating a "National Plan for Soil and Water Sustainable Management" based on the assemblage of existing regulations; intensifying the implementation of existing public policies and plans based on conservation agriculture (e.g., zero-tillage or integrated crop-livestock-forest systems); and including farmers' perceptions, technological improvements (e.g., biochar) and payments for ecosystem services programs in soil conservation planning. As regards the sustainability of crop-livestock systems, the studies alerted for the benefits of implementing a crop-livestock production system, which relate with increased productivity and income, as well as increased competitiveness and adaptability in the agribusiness market, besides the improved pasture. Besides, the studies referred that farmers with a previous experience in crop systems are more willing to adopt a crop-livestock system, because they likely have cultivable land, machinery and other assets. Finally, it was recognized that the assess to the ABC credit is also an important factor as is the existence of local grain buyers and storage and transportation facilities, whereas the lack of land tenure is a limitation. Finally, the main recommendation about land use transitions was to implement Participatory Impact Assessment to forecast sustainable expansion of competing land uses.

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CRediT authorship contribution statement

Carlos Alberto Valera: Writing – original draft, Methodology, Investigation, Data curation, Conceptualization. **Teresa Cristina Tarlé Pissarra:** Validation, Resources, Formal analysis. **Adriana Monteiro da Costa:** Software, Resources, Formal analysis, Data curation. **Luís Filipe Sanches Fernandes:** Writing – review & editing, Resources, Formal analysis, Data curation. **Fernando António Leal Pacheco:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

Data availability

Data will be made available on request.

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