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DERIELSEN BRANDÃO SANTANA

CARBON LOSSES DUE TO WATER EROSION AND GREENHOUSE GAS EMISSIONS IN COFFEE FARMING IN THE SOUTHERN STATE OF MINAS GERAIS

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Thesis presented as part of the requirements for obtaining the title of PhD in Environmental Sciences from the Universidade Federal de Alfenas.
Concentration area: Conservation and remediation of natural resources.
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DERIELSEN BRANDÃO SANTANA

“ Carbon losses due to water erosion and greenhouse gas emissions in coffee farming in the southern state of Minas Gerais ”

The undersigned examining board approves the thesis presented as part of the requirements for obtaining the title of PhD of Environmental Sciences from the Universidade Federal de Alfenas. Area of concentration: Conservation and Remediation of Natural Resources.

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to my girlfriend, fiancée and wife Aline;

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"Knowing that one does not know is the first step towards true knowledge."

(Confucius, date unknown)

GENERAL ABSTRACT

Concern about environmental issues is increasingly common, especially with regard to the impacts of global warming and climate change, both existing and predicted for the coming years. The projected scenarios for these phenomena are directly associated with the increase in the concentration of greenhouse gases (GHG) in the atmosphere. The main GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and water vapor. The main sources of GHG emissions in Brazil are related to deforestation and changes in land use for agriculture. In this scenario, agriculture contributes to the increase in emissions through enteric fermentation of cattle, agricultural mechanization and the use of nitrogen fertilizers. In view of this, modern agriculture increasingly requires the rational and sustainable use of natural resources and agricultural inputs, making it essential to adopt the best environmental practices in the management of crop management and the production process. Thus, the objective of this study was to identify the main sources and estimate GHG emissions and removals in three coffee production areas in southern Minas Gerais, in 2021, 2022, and 2023, considering direct and indirect emissions. The inventory was prepared based on the parameters of the GHG Protocol, of the Ministry of Science and Technology, the IPCC, in addition to specific regional data. The quantification of soil and carbon losses due to water erosion was also carried out, the calculation of the carbon stock under the coffee plantation and, finally, the carbon balance of the properties was prepared. As a result, the methodology indicated soil losses between 1.6 and 32 Mg ha^{-1} $year^{-1}$, with the lowest values obtained in native forest and the highest in exposed soil. Carbon losses ranged from 1 to 6600 kg ha^{-1} $year^{-1}$. Both values were considered low within the specialized literature. The inventory indicated that the GHGs generated in the study area were mainly due to the use of nitrogen fertilizers and the consumption of fossil fuels, especially diesel oil. The direct burning of wood in boilers also generated a significant amount of GHGs, although this burning is considered neutral in terms of emissions. Net CO_2 emissions were negative in the years analyzed, with removals greater than emissions. These values ranged from -3.5 to -9 t CO_2e in the period, demonstrating the sustainability of agriculture in the areas. These CO_2 removal values are within the range observed in other studies carried out in tropical climates. The coffee plantation areas were the most responsible for CO_2 removal, due to the high density of plants, frequent pruning and the agricultural management adopted. It is concluded that coffee production in the study units presents GHG emissions significantly lower than the global average, which highlights the importance of applied conservation management. However, these values can still be

reduced by replacing urea with non-urea nitrogen sources and by reducing direct firewood consumption.
Keywords: climate change; RUSLE; tropical; CO_2 removal; carbon footprint.

RESUMO GERAL

A preocupação com as questões ambientais é cada vez mais frequente, especialmente no que diz respeito aos impactos do aquecimento global e das mudanças climáticas existentes e previstas para os próximos anos. Os cenários projetados, diante desses fenômenos, estão diretamente associados ao aumento da concentração dos gases de efeito estufa (GEE) na atmosfera. Os principais GEE são o dióxido de carbono (CO_2), o metano (CH_4), o óxido nitroso (N_2O) e o vapor d'água. As principais fontes das emissões de GEE no Brasil estão relacionadas ao desmatamento e à mudança no uso da terra para agropecuária. Neste cenário a agropecuária contribui para o aumento das emissões pela fermentação entérica do bovinos, mecanização agrícola e pelo uso de fertilizantes nitrogenados. Diante disso, a agropecuária moderna exige, cada vez mais, o uso racional e sustentável dos recursos naturais e dos insumos agrícolas, tornando imprescindível a adoção das melhores práticas ambientais na condução dos tratos culturais e do processo produtivo. Assim, objetivou-se com o estudo identificar as principais fontes e estimar as emissões e remoções de GEE em três áreas de produção cafeeira no sul de Minas Gerais, nos anos de 2021, 2022 e 2023, considerando-se as emissões diretas e indiretas. O inventário foi elaborado com base nos parâmetros do GHG Protocol, do Ministério da Ciência e Tecnologia, do IPCC, além de dados regionais específicos. Também foi realizada a quantificação das perdas de solo e de carbono pela erosão hídrica, o cálculo do estoque de carbono sob cafezal e, ao final, elaborou-se o balanço de carbono das propriedades. Como resultado, a metodologia apontou perdas de solo entre 1,6 e 32 Mg ha^{-1} ano^{-1}, com os menores valores obtidos na mata nativa e os maiores no solo exposto. As perdas de carbono variaram de 1 a 6600 kg ha^{-1} ano^{-1}. Ambos valores foram considerados baixos dentro da literatura especializada. O inventário indicou que os GEE gerados na área de estudo decorreram principalmente do uso de fertilizantes nitrogenados e do consumo de combustíveis fósseis, especialmente o óleo diesel. A queima direta de lenha nas caldeiras também gerou quantidade significativa de GEE, embora essa queima seja considerada neutra em termos de emissões. As emissões líquidas de CO_2 foram negativas nos anos analisados, com remoções superiores às emissões. Tais valores variaram entre -3,5 e -9 t CO_2e no período, demonstrando a sustentabilidade da

agricultura nas áreas. Tais valores de remoção de CO_2 estão dentro da faixa observada em outros estudos realizados sob clima tropical. As áreas de cafezal foram as maiores responsáveis pela remoção de CO_2, devido à alta densidade de plantas, às podas frequentes e ao manejo agrícola adotado. Conclui-se que a produção de café nas unidades de estudo apresenta emissões de GEE significativamente inferiores à média global, o que evidencia a importância do manejo conservacionista aplicado. No entanto, esses valores ainda podem ser reduzidos com a substituição da ureia por fontes nitrogenadas não ureicas e com a diminuição do consumo de lenha direta.
Palavras-chave: mudanças climáticas; RUSLE; tropical; remoção de CO_2; pegada de carbono.

SUMMARY

1 GENERAL INTRODUCTION

Throughout the 20th century, population growth, industrialization, demand for fossil fuels, and changes in land use and coverage intensified climate change, generating adverse impacts and economic, social, and environmental implications (Kabir *et al.*, 2023). This fact led to increased discussions involving the consequences of anthropogenic actions on the planet, especially with regard to the increase in greenhouse gas (GHG) emissions and their concentration in the atmosphere (Rosa *et al.*, 2021).

The main GHGs are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor (Easterbrook, 2016; Cui *et al.*, 2018). Brazil is among the countries that emit the most GHGs, as Garofalo *et al.* (2022), mainly from agriculture and changes in land use and occupation (SEEG, 2024). The country is a major exporter of agricultural products and commodities, such as soybeans, coffee, sugarcane, cotton, eucalyptus, corn, as well as cattle, pigs, and poultry (IBGE, 2020). This is a result of the country's large land area, favorable climatic, hydrological, and soil conditions, and the use of technological agricultural practices (Nunes *et al.*, 2016).

Agriculture is one of the socioeconomic pillars of society. Environmentally, it is one of the only productive sectors capable of acting not only in mitigating, but also in actively removing CO_2 from the atmosphere. Through biological carbon fixation in plants, the accumulation of organic matter in the soil, and the adoption of conservation practices, it can function as an important carbon sink (Nazir *et al.*, 2024). Thus, in addition to producing food, fiber, and energy, agriculture directly contributes to offsetting emissions from sectors that are difficult to decarbonize, such as transportation, industry, and power generation, reaffirming its strategic role in combating climate change (Chen *et al.*, 2020).

Agribusiness accounted for 22% of GDP in 2024, close to R$2.6 trillion (CEPEA; CNA, 2025). Despite its relevance, agribusiness is associated with changes in land use and coverage, cattle farming, the application of nitrogen fertilizers, and the consumption of water resources and energy (Lynch *et al.*, 2021). Agriculture without conservation management practices can lead to negative environmental impacts, such as the intensification of water erosion, the silting of rivers and the reduction of atmospheric humidity and evapotranspiration, which harm the provision of ecosystem services (Badrzadeh *et al.*, 2022).

Changes in land use and land cover or agricultural management impact soil organic carbon (SOC) stocks, as Punhagui and John (2022) and climate change (Bernoux *et al.*, 2006). The global SOC stock is estimated at 1,350 Pg, a value higher than the atmosphere and vegetation combined (Georgiou *et al.*, 2022). Most of the SOC is located in the upper 2 m of the soil profile, as Lal (2004), which is more susceptible to human actions. The SOC stock is considered an indicator of sustainability in agricultural areas, as its high levels denote greater physical quality and better soil characteristics (Fließbach *et al.*, 2007). Therefore, agricultural management based on conservationist management practices is essential for sustainable development and the mitigation of negative environmental impacts.

One of the most important agricultural crops for Brazil is coffee. The country is the world's largest producer, with a production of 54 million bags of processed coffee in 2024, representing 31% of the world total (CONAB, 2024). Coffee cultivation was introduced in the country due to two factors: (i) slave labor, with entirely manual processes, which lasted for about two centuries, until the second half of the 20th century, and (ii) the deforestation of the primitive forests of the Atlantic Forest, in the state of São Paulo (Castro; Queiroz Neto, 2009).

Coffee is one of the agricultural crops most vulnerable to climate change (Pham *et al.*, 2019). Factors such as rising temperatures, changes in rainfall patterns, and accelerated climate variations directly influence flowering, fruiting, and grain quality processes, the incidence of pests, and water erosion, reducing productivity (Faraz *et al.*, 2023). It is the predominant agricultural activity in the South/Southwest region of Minas Gerais (CONAB, 2022), therefore, it requires the adoption of increasingly sustainable agricultural practices.

Coffee production is dependent on nitrogen fertilizers (Fenilli *et al.*, 2008). Nitrogen (N) is an essential element for the plant's cellular structure and vegetative development (IISD, 2014). However, the large-scale use of nitrogen fertilizers can cause eutrophication of water bodies, destruction of the ozone layer and intensification of global warming (Gatti *et al.*, 2021). Therefore, agriculture faces the challenge of maintaining high productivity and ensuring food security for a growing world population and, at the same time, reducing the environmental impacts arising from its practices (Thompson *et al.*, 2019). In this scenario, it is essential to develop studies to assess environmental impacts and optimize agricultural production systems.

An internationally accepted method for assessing environmental impacts is Life Cycle Assessment (LCA) (Nemecek; Schnetzer, 2012). LCA is a technique developed to measure the possible environmental impacts resulting from the manufacture, use and disposal of a product/service. The LCA study consists of four main phases: Definition of Objective and Scope; Life Cycle Inventory Analysis (LCI); Impact Assessment and Interpretation of Results.The accounting of greenhouse gas emissions is included within the LCI.

The accounting of greenhouse gas emissions is the compilation of data that cause environmental impacts (Coltro, 2007). It makes it possible to establish what is the most significant contribution to GHG emissions through input and output data, evaluate the implementation of process improvements, readjust the operational management of an agricultural production system and propose compensation measures through the application of decarbonization techniques (Rebitzer *et al.*, 2004).

LCA studies began in the mid-1970s following the oil crisis (Renouf *et al.*, 2017). This crisis led society to question the exploitation of natural resources. From 1990 onwards, such studies were expanded, driven by the standardization provided by the ISO 14000 series. The international standardization work of LCA by ISO involved more than 300 experts from 29 countries (ABNT, 2009). Since the establishment of ISOs, the agricultural industry has sought increasingly sustainable guidelines and policies, combined with increased consumer environmental awareness, environmental certifications and market competitiveness (Kulak *et al.*, 2016).

The area where the study is conducted is owned by Ipanema Coffees, a company that has actions that aim to legitimize and promote more sustainable agricultural production. Studies already carried out on soil and SOC losses resulting from water erosion can be cited, revealing concern about environmental issues (Mendes Júnior *et al.*, 2018; Tavares *et al.*, 2019; Bolleli *et al.*, 2020; Lense *et al.*, 2020, 2022; Santana *et al.*, 2023).

The study also seeks to demonstrate how feasible and/or possible it is to establish readjustments in the operational management of an agricultural system, aiming at reducing GHG emissions, as well as offsetting them through the application of forest restoration techniques. The study also meets the objectives proposed within the Postgraduate Program in Environmental Sciences at the Universidade Federal de Alfenas, considering its social, technological and scientific relevance. Given this scenario, this research had the general objective of carrying out the GHG inventory and carbon balance (C) over 3 years (2021, 2022 and 2023) in coffee agricultural production areas at Ipanema Coffees units.

2 THEORETICAL BACKGROUND

2.1 CLIMATE CHANGE AND COFFEE

The agricultural sector occupies 40% of the Earth's surface (Foley *et al.*, 2005). This sector is expected to be the most vulnerable to climate change (Parker *et al.*, 2019), imposing major challenges on farmers. Food production is governed by the climate. Climate change will lead to reduced productivity, faster food spoilage, temperature variations in the aquatic habitats of fish and shellfish species, and reduced food supply for cattle, pigs, and poultry (Mbow *et al.*, 2019; Godde *et al.*, 2021). Studies indicate that, without increasing soil C through fertilization and/or manure and genetic improvement, each 1°C increase in the global average temperature will reduce, on average, global wheat production by 6.0%, rice by 3.2%, corn by 7.4% and soybean by 3.1% by the end of the 21st century (Zhao *et al.*, 2017). In Brazil, climate change projections for the end of the 21st century indicate an increase in average temperature, especially in the Center-West of the country, as in Chou *et al.* (2014); they also suggest more dry days and higher average temperatures, above 34°C (Assad *et al.*, 2004; Marengo *et al.*, 2009, 2010, 2012). There will also be impacts on annual precipitation, which will increase in the Western and Southern Amazon of Brazil and decrease in the Eastern and Northeastern Amazon, Central-West and Southeast regions (Marengo *et al.*, 2009; Marengo *et al.*, 2012).

Studies conducted by Assad *et al.* (2016) evaluated the impact of climate change on Brazilian agriculture. They found a 65.7% reduction in the area suitable for soybean production. The impacts on the area suitable for corn production would be even more intense, resulting in an 84.9% reduction by 2050, mainly affecting corn produced as a second crop, the so-called safrinha. Assad *et al.* (2004) and Camargo (2010) also predicted a 24% to 95% reduction in the areas suitable for coffee growing in Minas Gerais in optimistic and pessimistic scenarios of increased temperature, respectively. Therefore, agricultural practices will be necessary to promote efficient use of nitrogen fertilizers and other inputs, along with changes in human consumption patterns and the adoption of decarbonization practices (Rosa; Gabrielli, 2023).

One of the main global commodities is coffee, with an estimated annual market value of US$ 200 billion (Rotta *et al.*, 2021). Coffee is grown on 12.5 million farms, date by Fairtrade Foundation (2022) and employs 125 million people worldwide (Siles; Cerdán; Staver, 2022). Most coffee production is carried out by small producers on areas of 5 ha or less. More than half of production is concentrated in American countries (Bilen *et al.*, 2023).

Originating in East Africa, coffee production was widespread in tropical and subtropical countries, and is of great economic and cultural importance (IISD, 2014). It was introduced in Brazil in the mid-18th century and became one of the country's main economic activities. Between 1991 and 2019, Brazilian production grew by 130% (ICO, 2020).

The area occupied by Brazilian coffee production is approximately 2.25 million hectares (CONAB, 2024). Since colonization, the coffee sector has assumed relevance in generating income and occupying the territory. National coffee production began on land with good natural fertility, with the first seedlings planted in the province of Pará (Belém) (Castro; Queiroz Neto, 2009). Later, it was extended to the soils of the Cerrado, which have very good physical characteristics, but with low natural fertility and depend on correction and fertilization practices (Castro; Queiroz Neto, 2009).

Coffee is one of the cultivars most sensitive to climate change (Ahmed *et al.*, 2021). Around 60% of wild coffee species are threatened with extinction (Davis *et al.*, 2019). Studies indicate that climate change could raise temperatures in cultivation areas, alter precipitation patterns and intensify climate variability events (Malhi; Kaur; Kaushik, 2021). With such aggravating factors, there would be a reduction in areas suitable for cultivation, a decrease in production and an increase in the incidence of pests and diseases (Kumar *et al.*, 2022). In view of these issues, certification systems have increasingly emerged in the coffee market.

Coffee certificates are validations that aim to attest to the greater quality and sustainability of the product. Such certifications encourage the adoption of better production practices, minimize environmental damage and increase producers' income (IISD, 2014). Coffee production in compliance with sustainability standards grows 26% per year (IISD, 2014). The increase in the purchase of sustainable coffees between 2019 and 2020 was 53.1% (Moda *et al.*, 2022). The largest producers were Brazil, Vietnam, Colombia, Honduras and Mexico. The main certifications are Fairtrade (FT), Organic, Rainforest Alliance/UTZ, 4C Common Code/Global Coffee Platform (4C/GCP) e Starbucks' C.A.F.E. Practices and Nespresso's AAA Guidelines (Moda *et al.*, 2022).

Brazil is currently the world's largest supplier of certified coffee (MAPA, 2023). The main export destinations are the United States, Germany, Belgium, Italy, Japan, and the United Kingdom (MAPA, 2023). Brazilian coffee cultivation, aligned with sustainable agricultural practices, has positioned the country as an international reference in the production of high-quality food. Despite this, coffee production, depending on management practices, can directly contribute to GHG emissions, especially N_2O (Bentzon-Tarp *et al.*, 2023).

2.2 GREENHOUSE GAS (GHG) EMISSION

Coffee plants are demanding in terms of nutrition, especially nitrogen (N). N is a component of the cellular structure of plants and is essential for the development of flowering buds and vegetative formation (Fenilli *et al.*, 2008). Brazil is one of the largest consumers of N in the world (IFA, 2020). N application varies depending on the phenological phase of the plant, expected productivity, and soil fertility (Sarkis *et al.*, 2023). Each hectare of coffee plantation requires 200 to 500 kg of N per harvest, generally divided into 3, 4, or 5 applications (Ribeiro; Guimarães; Alvarez, 1999; de Souza *et al.*, 2023). N application is carried out via mineral nitrogen fertilization (ammonium sulfate or nitrate, urea) and organic nitrogen fertilization (animal waste, straw, coffee husks, sewage sludge, among others). Only 25% to 50% of N is absorbed by plants due to losses through ammonia (NH_3) volatilization, nitrate leaching, and nitrous oxide (N_2O) emissions (de Vries *et al.*, 2023).

N_2O is responsible for approximately 6% of global anthropogenic GHG emissions (Chiaravalloti *et al.*, 2023). N_2O emissions come from natural sources (soils, oceans, and forest fires), but are increased by anthropogenic activities, including the use of nitrogen fertilizers (Pan *et al.*, 2022). In soil, N_2O emissions are generated through two microbial processes: nitrification and denitrification (Snyder *et al.*, 2009). The amount of N_2O produced depends on the range of oxygen (O_2) concentrations in the soil, the texture and relief, the amount of ammonium (NH_4^+) available for nitrification and the amount of nitrate (NO_3^-) for denitrification (Firestone, 1982; Granli; Bøckman, 1994; Lam *et al.*, 2018).

Despite its extreme importance for agricultural production, the large-scale use of nitrogen fertilizers is associated with environmental impacts that make ecosystems, human health and agricultural production itself vulnerable. The agricultural sector is responsible for 87.2% of N_2O emissions, mainly from the management of animal waste and agricultural soils (Cerri *et al.*, 2009). The concentration of N_2O in the atmosphere increased from 270 ppb during the pre-industrial period to 319 ppb in 2005 and 332 ppb in 2019 (Signor; Cerri, 2013; Chiaravalloti *et al.*, 2023). According to Vishwakarma, Zhang and Muller (2022), the global demand for nitrogen fertilizers is likely to reach 204 million t year^{-1} by 2050, which would aggravate N_2O emissions (He *et al.*, 2023; Walling; Vaneeckhaute, 2020).

N_2O has a global warming potential 265 to 298 times greater than CO_2 and contributes to the destruction of the ozone layer (Myhre *et al.*, 2013). N_2O emissions account for 58% of total human-induced emissions and are estimated to increase by 35% to 60% by 2030 (relative to 1990) (Capa *et al.*, 2015). The largest source of N_2O in nitrogen fertilizers comes from urea (van der Weerden, 2016; Menegat; Ledo; Tirado, 2022).

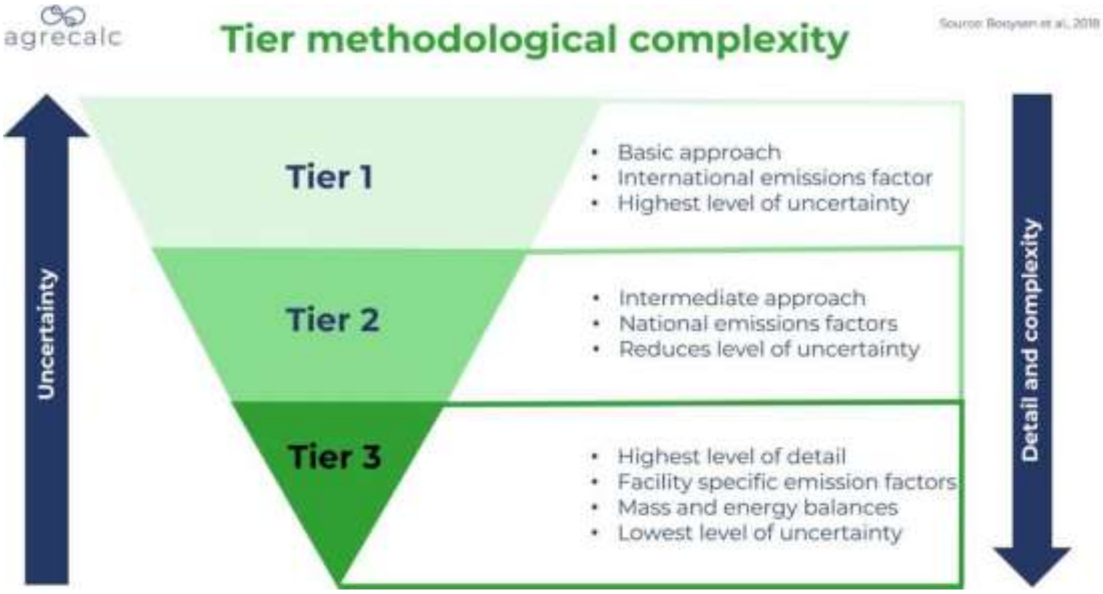
Urea is the most widely used nitrogen fertilizer in Brazil and worldwide (Hao *et al.*, 2021; Leite *et al.*, 2023). Approximately 55% of global nitrogen fertilizer production is urea-based (IFA, 2017). Urea fertilizers have a high concentration of N (approximately 45%), lower cost, and high solubility (Minato *et al.*, 2020). However, 25% of the urea applied to the soil surface is converted into ammonia (NH_3) and volatilized into the atmosphere (Leite *et al.*, 2023). This rate is even higher in tropical countries due to higher temperatures, greater rainfall, and wetter soils (Wang; Köbke; Dittet, 2020). N losses also represent an economic loss for farmers due to fertilizer replacement. Therefore, it is essential to increase the efficiency of N use.

Increasing N efficiency can be achieved in different ways. One of them corresponds to good agricultural practices: correct application of fertilizers with soil tests to determine the necessary amount, crop rotation, and the no-till system (Alam *et al.*, 2020; Mondal; Chakraborty, 2022). Another is the inclusion of chemical products in fertilizer formulations in order to delay N transformation. Such products can influence NH_3 volatilization, nitrate (NO_3^-) leaching, and the reduction of N_2O emissions (Li *et al.*, 2015; Minato *et al.*, 2020). The most commonly used products are urease and nitrification inhibitors (Paustian *et al.*, 2016; Lutz; Stoorvoge; Müller, 2019). Many farmers have opted for these products, which, despite their higher prices, generate environmental benefits and add economic value to the product (Li *et al.*, 2017).

2.3 GREENHOUSE GAS INVENTORY

The inventory is based on the Greenhouse Gas Protocol Initiative (GHG Protocol). It is the most efficient method used worldwide for conducting inventories and is accepted by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2006; 2019). This method was developed in the United States by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). Its main objective is to quantify and manage GHG emissions/removals. The inventory is based on international standards that use the Tier classification (Figure 1) (IPCC, 2019). The Tier classification ranges from 1 to 3 and refers to the level of data refinement. Tier 1 is considered general data; Tier 2 is country-specific data; and Tier 3 is regional data, with a greater degree of detail.

Figure 1 – Flowchart for identifying Tier classification.



Source: Booysen *et al.* (2018).

The sources of GHG emissions and removals and the quantities reported follow the GHG Protocol model, categorized into scopes 1, 2, and 3 (IPCC, 2019). These scopes are classified according to the level of responsibility of the sources – direct sources (owned or controlled by the inventory organization) and indirect sources (owned or controlled by another organization, but resulting from the activities of the inventory organization) (WRI; UNICAMP, 2015). The scopes are classified as follows:

Scope 1: these are direct emissions from sources owned or controlled by the inventory organization. They can be divided into mechanical sources – sources that emit GHGs through the combustion process. Examples of mechanical sources include harvesting equipment and trucks for transportation; Non-mechanical sources – sources that emit GHGs through biochemical processes. Examples of non-mechanical sources include enteric fermentation of livestock and nitrogen fertilization; changes in land use – emissions occur when native vegetation is removed for agricultural purposes, for example; or when a degraded pasture area is converted to planted forest, for example.

Scope 2: Indirect emissions from the purchase of electricity consumed by the company.

Scope 3: All other indirect emissions not reported in Scope 2. Scope 3 emissions are a consequence of the company's activities, but occur in sources that are not owned or controlled by the company. Examples of Scope 3 sources include emissions from employee commuting, effluent treatment, business travel, emissions from remote work (new category) or the transportation of herbicides.

As stipulated by the GHG Protocol, all GHGs are quantified and reported. This quantification is performed using equations obtained from the literature, which require the input of variables, such as the quantity of product used and its emission factor. In the end, all GHGs are converted into carbon dioxide equivalent (CO_2e).

Carbon dioxide equivalent (CO_2e) is a standardized international measurement used to equivalently convert emissions of all GHGs into CO_2. This equivalence considers the so-called Global Warming Potential (GWP) of GHGs. The most widely used metrics today are GWP-100, present in AR5 (Fifth Assessment Report), in IPCC (2013) and AR6 (IPCC, 2021). GWP-100 is the capacity of that gas to absorb heat in the atmosphere for 100 years (IPCC, 2013). This capacity is compared to the same heat absorption capacity of CO_2 and from there the amount of CO_2e that would be emitted is estimated (IPCC, 2013). The formula for calculating CO_2e is the multiplication of the amount of the GHG in question by its GWP and the result is given in metric tons per year. GWP-100 data follows in Table 1 for some GHGs.

Table 1 **-** Global Warming Potential (GWP) of each greenhouse gas (GHG) included in the scope tool

GHG	**GWP**
CO_2	1.0
CH_4 – fossil	29.8
CH_4 – no fossil	27.0
N_2O	273.0

Source: IPCC (2021).

The last stage of the GHG inventory is the C balance, which represents the net difference between the C emitted and the C removed.

2.4 CARBON REMOVAL

With the advent of climate change and global warming, many alternatives have emerged with the aim of increasing the carbon stock stored in soils, oceans and terrestrial biomass. Such alternatives are called “nature-based solutions” (Nesshöver *et al.*, 2017; Haughey *et al.*, 2023). The main one is the carbon removal or sequestration technique.

Carbon removal is defined as the process of removing carbon dioxide from the atmosphere. This process can be carried out (i) naturally, by preserving carbon sinks, through the absorption of CO_2 by vegetation through photosynthesis and/or by absorption by the ocean and soil, as in Lal (2008) and (ii) through clean energy technologies, focused on carbon capture and storage and the production of green hydrogen (Ali *et al.*, 2022). Vegetation preservation and reforestation are efficient practices for increasing C removal.

According to a study carried out by the Iinstituto Totum and the Escola Luiz de Queiroz de Agricultura (ESALQ) of the Universidade de São Paulo, in partnership with the SOS Fundação Mata Atlântica, it is estimated that each tree in the Atlantic Forest absorbs 163.14 kg of CO_2 equivalent over its first 20 years (Rosa, 2013).

Increasing carbon removal from the soil through agricultural practices is essential to reducing GHG emissions. For example, management, (i) through the maintenance of plant residues, frequent pruning with control, organic fertilization, the application of biochar and reduced soil disturbance, which increase the stability of soil aggregates, renew the processes of accumulation of organic matter, improve the structure and resistance against splashing or splashing of soils (Ogle *et al.*, 2019); (ii) contour cultivation, which creates mechanical resistance to surface runoff and reduces nutrient mineralization (Doraiswamy *et al.*, 2007); (iii) the agroecological planting system with shade and crop diversity and rotation, which generate greater fixation of N and C in the soil, improved water retention capacity, reduced susceptibility to water erosion and decomposition of organic matter with less dependence on inputs and fertilizers (Lugo-Pérez *et al.*, 2023); (iv) the preference for non-ureatic, controlled-release fertilizers; or ureatic fertilizers with urease inhibitors; (v) efficient irrigation management, with lower water consumption or reuse systems and (vi) reduced deforestation and recovery of degraded areas.

2.5 WATER EROSION

Soil is an essential resource for life on Earth. Its functions include climate regulation, water purification, contaminant degradation, nutrient cycling, and carbon sequestration (FAO; ITPS, 2015). Humans obtain 99.7% of their food from the land (Pimentel, 2006). Despite its importance, soils have been continually degraded. Approximately 1% of the global land area is degraded annually (Scholes; Scholes, 2013).

One of the phenomena that degrades soils is water erosion. It consists of a natural geological process that involves the disintegration, transport, and deposition of sediments (Sayão *et al.*, 2020); however, it has been intensified by human actions, such as accelerated changes in land use and coverage and inadequate agricultural management (Castro *et al.*, 2022). Precipitation characteristics, intrinsic soil properties, topography and climate also influence water erosion (Ganasri; Ramesh, 2016; Tuo *et al.*, 2023). The consequences of water erosion are the loss of soil and nutrients, silting of water bodies, pollution of river waters, reduction of agricultural production potential and interference in the carbon cycle (Fang, 2020; Lal, 2022). The main problem caused by water erosion occurs when the loss of the topsoil exceeds its formation rate (Di Stefano *et al.*, 2023). Soil regeneration is unfeasible on a human time scale. In addition to environmental damage, there is also an economic cost, since compensating for nutrient losses caused by erosion requires high investments in fertilizers (Telles; Guimarães; Dechen, 2011). Therefore, in order to achieve environmental and agricultural sustainability, erosion rates must be reduced to levels close to zero (FAO, ITPS, 2015).

Water erosion is related to climate change, as in Nearing *et al.* (2004) and is more frequent in tropical countries, which have higher rainfall rates (FAO; ITPS, 2015). Although there is no exact consensus on the global extent of water erosion, there is already a considerable amount of agricultural land with reduced productivity (Campbell *et al.*, 2017). According to Gibbs and Salmon (2015), 1 to 6 billion hectares of the Earth's surface not occupied by ice are degraded at different levels. Such degradation increases the vulnerability of carbon (C) to transport by water erosion (Lal, 2022).

Soil is the largest terrestrial reservoir of C (Lin *et al.*, 2023). There are discrepancies regarding the global soil organic carbon (SOC) stock, which varies between 504 and 3000 Pg (Scharlemann *et al.*, 2014), a value higher than that of vegetation and the atmosphere combined (Georgiou *et al.*, 2022). Considering only the 0-30 cm depth layer, the SOC stock is 800 Pg (Cerri *et al.*, 2006).

Water erosion alters and redistributes SOC levels. Not only SOC, but also methane (CH_4) and nitrous oxide (N_2O), two of the main GHGs (Lal, 2020). Globally, SOC transported by erosion is estimated to range from 0.3 to 5.7 Pg C year^{-1} (Lal, 2003; Berhe *et al.*, 2007; Quinton *et al.*, 2010; Chappell; Baldock; Sanderman, 2015; Lin *et al.*, 2022). Most of the eroded soil comes from agricultural lands, as in Nearing *et al.* (2017), which also carry nutrients, phosphorus and potassium. Over the 20th century, erosion in agricultural lands increased by 17%; therefore, studies of water erosion with an impact on SOC dynamics are essential (Yang *et al.*, 2003).

The study of water erosion can be carried out by predictive models. Over the years, such models have been developed and improved. These models enable the spatialization of erosion and the estimation of soil loss rates (Gelagay; Minale, 2016). Through mathematical equations, the models can simulate water erosion in space-time dimensions, playing an essential role in agricultural planning and in the maintenance of ecosystem services (Regan *et al.*, 2019).

One of the main models used to study water erosion is RUSLE (Revised Universal Soil Loss Equation) (Renard *et al.*, 1997). RUSLE estimates the annual soil loss rates from sheet and rill erosion, not accounting for sediment deposition in gullies and erosion on the banks and bottoms of the channel (Ganasri; Ramesh, 2016). It is the most widely used model in the world due to the speed in obtaining results, the simplicity of the input database and the acceptable accuracy. The RUSLE equation is as follows: (Equation 1).

$$A = R \times K \times LS \times C \times P \tag{1}$$

Where: A = average annual soil loss, in Mg ha^{-1} year^{-1}; R = rainfall erosivity factor, in MJ mm ha^{-1} h^{-1} year^{-1}; K = soil erodibility factor, in Mg ha^{-1} MJ^{-1} mm^{-1} ; LS = topographic factor, dimensionless; C = soil use and management factor, dimensionless; P = conservation practices factor, dimensionless.

RUSLE was developed in 1997 (Renard *et al.*, 1997). It is an improved revision of the USLE (Universal Soil Loss Equation) , but without the use of experimental field study plots (Wischmeier; Smith, 1978). RUSLE is a consequence of technological advances in Geographic Information Systems (GIS), remote sensing and the most modern geostatistical methods, overcoming the geographic and climatic restrictions of other models and facilitating the obtaining of results (Ayer *et al.*, 2015).

The R factor is defined as the capacity of rainfall to cause soil loss (Renard *et al.*, 1997). It is an average, multi-year index that calculates the kinetic energy and intensity of precipitation to describe its effects on water erosion and soil loss (Tu *et al.*, 2023).

The K factor expresses the susceptibility of the soil to water erosion (Silva *et al.*, 1999). A soil with high erodibility will suffer more erosion than a soil with low erodibility, both under the same conditions of slope, vegetation cover, control practices and precipitation. Therefore, erodibility is related to the mineralogical, chemical, morphological, physical and biological properties of the soil (Silva, 1999; Brady; Weil, 2013).

The L factor is the ratio of soil losses between any ramp and a standard 22.3 meter ramp, both under the same conditions. The S factor is the ratio of soil losses between any slope and a 9% slope for the same ramp length, both under the same conditions. These factors directly influence soil losses, since the increase in ramp length and slope intensifies the speed of surface runoff water flow (Renard *et al.*, 1997).

The C factor represents soil use and management. It is one of the factors most influenced by human actions (Hitouri *et al.*, 2023). It consists of the ratio between soil losses in a land under a certain vegetation cover and management and the corresponding losses in a land kept continuously uncovered in fallow (Panagos *et al.*, 2015).

The P factor represents conservation practices, which can be of soil, mechanical and vegetative origin and are intended to reduce the rate of surface runoff, modifying its flow, intensity and direction mitigating the potential for erosion and maximizing the yields of agricultural activity (Van Vliet, 2002).

C and P vary from close to zero to one: the closer to 0, the greater the protection of vegetation against the erosion process (value commonly adopted for native forests); intermediate values indicate different degrees of susceptibility to the erosion process; the closer to 1, the less protection of vegetation against the erosion process (value commonly adopted for exposed soil) (Vijith; Hurmain; Dodge-Wan, 2018).

3 PAPER I - Soil and organic carbon losses by water erosion in coffee-growing areas in southern Minas Gerais, Brazil

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Soil and organic carbon losses by water erosion in coffee production areas in southern Minas Gerais, Brazil

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Abstract: Organic carbon performs essential functions in soils, which act as sources or sinks of atmospheric organic carbon. Agricultural management affects the carbon cycle in the soil, with effects on climate change. One of the crops most vulnerable to climate change is coffee. Brazil is the world's largest coffee producer, with a predominance of management under a conventional system, with sloping terrain and the absence of conservationist practices. The absence of conservationist practices increases in soil loss rates due to water management and carbon emissions, as well as a reduction in coffee production. This paper intended to estimate soil and organic carbon losses by RUSLE in coffee farms in southern Minas Gerais, south-eastern Brazil. Data were obtained from fieldwork, laboratory analysis, and cartographic products. The results indicated, exclusively for coffee crops, soil and carbon losses between 7 and 32 Mg ha^{-1} $year^{-1}$ and 87 and 460kg ha^{-1} $year^{-1}$, respectively. However, the highest soil losses occurred on sloping terrains with eucalyptus plantations located downhill, and the lowest losses occurred on flat land with native forests. Organic carbon losses were linked directly to soil losses, as a result from the land practices, slope and agricultural management adopted. These results can be used for the planning and priority definition of areas needing conservationist practices, such as green manuring, planting in contour and maintaining of vegetation between coffee rows, which are already used in some sites of the study area.

Key words: RUSLE, land use, soil organic matter, agricultural systems

1. Introduction

The problem with land degradation, water pollution and with decrease and lose of natural resources is one of the key environmental problems. Soil pollution by heavy metals due to agricultural and industrial practices is a serious environmental concern today (Yazdanpanah-Ravari *et al.*, 2022). Over the course of the 20th century, population growth and the expansion of human activities led to an increase in per capita water consumption (Hosseini Beryekhani and Parsa, 2021). Water is essential to humanity, but it is associated with soil depletion through water erosion, which is one of the leading causes of soil degradation worldwide (Spalevic *et al.*, 2020). It is a natural process intensified by human lifestyle (Khosravi *et al.*, 2023). The main consequences of water erosion are losses of soil, nutrients, soil organic matter (SOM), and soil organic carbon (SOC) (Dechen *et al.*, 2015). Approximately 75 Pg of soil is eroded annually from arable land worldwide at a projected economic value of US$ 400 billion (Borrelli *et al.*, 2017). In Brazil, it is estimated that approximately 3 Pg is lost per year, with an estimated loss of US$ 15.7 billion, considering the replacement costs of fertilizers and limestone (Polidoro *et al.*, 2021).

The carbon reserves in the Earth's biosphere have been significantly altered in recent centuries due to anthropogenic disturbances, such as the transformation of natural lands into agricultural systems, which regularly results in the loss of carbon from the soil. (Janes-Bassett *et al.*, 2021). The global SOC stock is in the order of 1350 Pg, which is greater than that of the atmosphere and vegetation cover combined (Georgiou *et al.*, 2022). Most of the SOC is in the first 2 m of the soil profile (Lal, 2004). The SOC content is conditioned by the parent material, climate, slope, structure, texture, amount of SOM, vegetation, and

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management (Muhammed *et al.*, 2018; Koç *et al.*, 2020). It is an indicator of the sustainability of the management adopted in agricultural areas. High SOC rates denote higher soil physical quality and better soil characteristics (Davis *et al.*, 2018) and contribute to mitigating climate change and extreme weather phenomena (Jordahl *et al.*, 2023). Water erosion causes the oxidation of SOC, which releases carbon dioxide (CO_2) into the atmosphere. Such emissions, even at small rates, are sufficient to elevate greenhouse gases (GHG) and adversely affect climate change (Friedlingstein *et al.*, 2020). Worldwide, between 42 and 78 Pg of SOC have been lost in the last century due to badly management practices and erosion (Lal, 2004). In this scenario, land conversion from native forest to agricultural systems can emit 20% to 40% of the initial SOC stock over dozens of years of cultivation (Polyakov and Lal, 2008). Therefore, the incorporation of sustainable agricultural practices is crucial (Sedighi *et al.*, 2022), and thus, the loss of soil organic matter (SOM) through intensive cultivation is the focus of studies that encompass climate change and food security (Jakab *et al.*, 2023). In this scenario, coffee is one of the most important commodities produced in Brazil. Production began in the 18th century, and in the 20th century it became the world's largest coffee producer and exporter (Castro and Queiroz Neto, 2009). Minas Gerais state accounts for approximately 50% of national production. However, for historical and cultural reasons, cultivation characterized by extensive land use predominates, with inadequate conventional production systems, such as the absence of permanent preservation areas and mechanical, edaphological, and vegetative conservation practices, which result in soil degradation by increasing water erosion and GHG emissions (Aslam *et al.*, 2021).

Water erosion impact studies can use digital simulation models. Such models allow for low-cost applications, quickness and good accuracy compared to traditional empirical models (Liu *et al.*, 2021). The most commonly used model is the Revised Universal Soil Loss Equation (RUSLE) (Renard *et al.*, 1997), which allows spatialization and estimation of soil losses and SOC. Its success worldwide stems from its low input requirements and applicability at regional scales (Halder, 2023). However, there is still a lack of studies on SOC losses caused by water erosion (Wang *et al.*, 2022). In view of the above and considering the different land uses in coffee plantation areas in the south of Minas Gerais, soil and SOC losses were estimated by RUSLE.

2. Materials and methods

2.1 Study area

The research was carried out at the Conquista coffee producing units (Conquista Farm) in Alfenas Municipality (Figure 1a), Capoeirinha (Capoeirinha Farm) in Alfenas and Machado Municipalities (Figure 1b), and Rio Verde (Rio Verde and Pinheirinho Farms) in Conceição do Rio Verde and Cambuquira Municipalities (Figure 1c), owned by company Ipanema Coffees.

Alfenas and Machado are part of the Guaxupé Massif (Hasui, 2010). The slope of rounded and gentle hills is partially conditioned by the lithological type, with

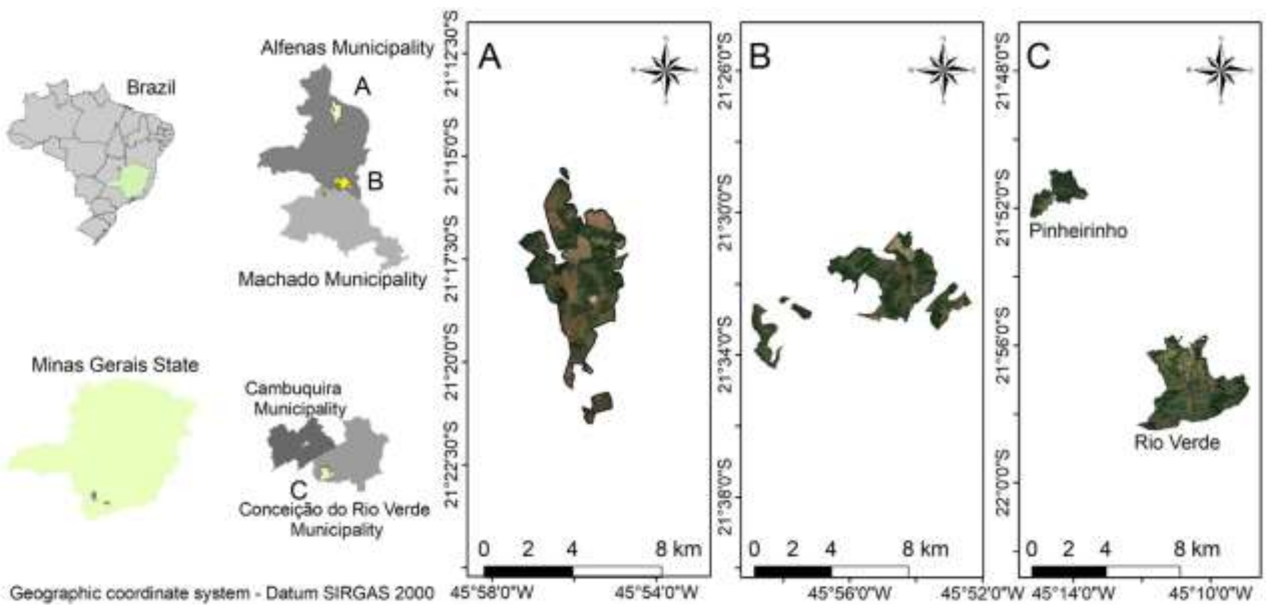

Figure 1. Location maps of Conquista (a), Capoeirinha (b), and Rio Verde and Pinheirinho (c) farms.

mountains supported by gneisses and quartzites; the lower altitude and flat areas consist of granulites, orthogneiss and paragneiss (CPRM, 2020). Clayey colluvial and eluvial soils predominate in large areas without rocky outcrops (CPRM, 2020). Native vegetation is formed by the Cerrado with transition zones to the Atlantic Forest (CPRM, 2020).

Cambuquira and Conceição do Rio Verde are located on the outskirts of the Mantiqueira mountain range, next to the Rio Verde Depression, and between the Lambari, Baependi and Rio Verde Rivers (Brasil, 1983). The area is characterized by elevations with irregular relief, hills with gentle slopes and shallow valleys with broad bottoms with river plains and alluvial terraces. The region is part of the Atlantic Forest biome (Silva *et al.*, 2021).

According to Köppen (1936), the areas are classified as humid subtropical climate (Cwb). Alfenas and Machado have an average annual temperature of 21.2 °C and average annual rainfall of 1500 to 1750 mm. On the other hand, Conceição do Rio Verde and Cambuquira have a mean annual temperature of 20.1 °C and 19.9 °C and mean annual rainfall of 1660 to 1900 mm and 1690 to 1920 mm, respectively (Alvares *et al.*, 2013).

The Conquista farm has an area of 2045 ha, of which 82.26% is coffee cultivation, 14.54% is native forest, 1% is eucalyptus, 0.91% is pasture, 0.88% is facility area and 0.41% is water bodies. The Ferralsol (Red Latosol) type and the gentle-wavy slope predominate, with altitudes ranging from 760 to 890 m. The Capoeirinha farm has an area of 1772 ha, of which 68.07% is coffee cultivation, 23.08% is native forest, 5.26% is eucalyptus, 1.8% is water bodies, 0.93% is pasture and 0.86% is facility area. Ferralsol (Red and Red–yellow Latosol) and undulating slope predominate, with altitudes ranging from 781 to 971 m. The Rio Verde and Pinheirinho farms have a total area of 1666 ha, of which 45.28% is native forest, 44.90% is coffee cultivation, 8.29% is pasture, 0.60% is facility area, 0.49% is eucalyptus and 0.44% is water bodies. Acrisol (Red Argisol) and Ferralsol (Red–yellow Latosol) predominate, the slope is gentle-wavy, and the altitudes range from 839 to 1341 m.

Mechanized harvesting is 100% at the Conquista, 98% at the Capoeirinha and 69% at the Rio Verde. Manual harvesting, in turn, occurs in approximately 12% of the coffee area, especially in the steeper slopes of the Rio Verde and Pinheirinho farms. In the Conquista, spacing varied from 3.5 to 4.0 m between planting lines and from 0.5 to 1.0 m between plants; in the Capoeirinha from 2 to 4.8 m and 0.5 to 1.5 m; and in the Rio Verde from 2 to 4 m and from 0.5 to 2 m, respectively.

2.2 Methodological procedures

All maps were made in ArcGIS 10.8 software (ESRI, 2020). The land use map was based on field observations, Landsat-8 TM (Thematic Mapper) satellite images, orbit 219/75, TM6, TM5, and TM4, obtained on USGS digital platform[1] from 2023 and the MapBiomas collection 7 from 2021[2]. The data were compared and validated in fieldwork, confirming the absence of significant changes in land use. The classes of native forest, coffee, eucalyptus, water bodies, pastures, and facilities were identical (Figures 2a–2d).

The soil class map was produced according to McBratney *et al.* (2003), based on the Minas Gerais Soil Map, at a scale of 1:650,000 (UFV *et al.*, 2010). Next, we mapped the indiscriminate floodplain soils (IFS) with delimitation adjacent to the water bodies (Figures 3a–3d). The soil classification was based on Santos *et al.* (2018) and was correlated with the World Reference Base for Soil Resources[3] (WRB). The slope was processed using a digital elevation model (DEM) with 30 m spatial resolution from the ALOS PALSAR mission (Figures 4a–4d), obtained from the L band with images from February 2011 (absolute orbit n° 27875) and extracted from the NASA digital platform[4].

The slope was classified, according to EMBRAPA (1979), as flat (0–3%), gently undulating (>3–8%), undulating (>8–20%), strongly undulating (>20–45%), mountainous (>45–75%), and rugged (>75%) (Figures 5a–5d).

2.3 Revised Universal Soil Loss Equation (RUSLE)

The RUSLE was used to estimate and spatialize annual soil losses. The RUSLE considers the factors of rainfall erosivity, soil erodibility, slope length and steepness, land use and management, and conservation practices (Equation 1).

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the average annual soil loss rate in $\mathrm{Mg\ ha^{-1}\ year^{-1}}$; R is the rainfall erosivity factor in $\mathrm{MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}}$; K is the soil erodibility factor in $\mathrm{MJ^{-1}\ mm^{-1}}$; LS is the topographic factor expressing slope length and steepness (dimensionless); C is the factor for land use and management (dimensionless); and P is the factor for conservation practices (dimensionless) (Wischmeier and Smith, 1978).

[1]USGS United States Geological Survey (2023). EarthExplorer [online]. Website www.earthexplorer.usgs.gov [accessed 11 March 2023].

[2]Projeto MapBiomas (2021). Map Biomas Project - Collection 7 Annual Series Maps of Land Use and Land Cover in Brazil [online]. Website https://brasil.mapbiomas.org/download [accessed 17 May 2023].

[3]USS International Union of Soil Sciences (2015). World Reference Base for Soil Resources (WRB) Sistema Universal Recognized by the International Union of Soil Science (IUSS) and FAO [online]. Website. http://www.fao.org/3/a-i3794e.pdf. [accessed 16 January 2023].

[4]ALOS PALSAR (2015). Radiometric_Terrain_Corrected_low_res; Includes Material © JAXA/METI 2007 [online]. Website. https://doi.org/10.5067/ JBYK3J6HFSVF [accessed 17 March 2023].

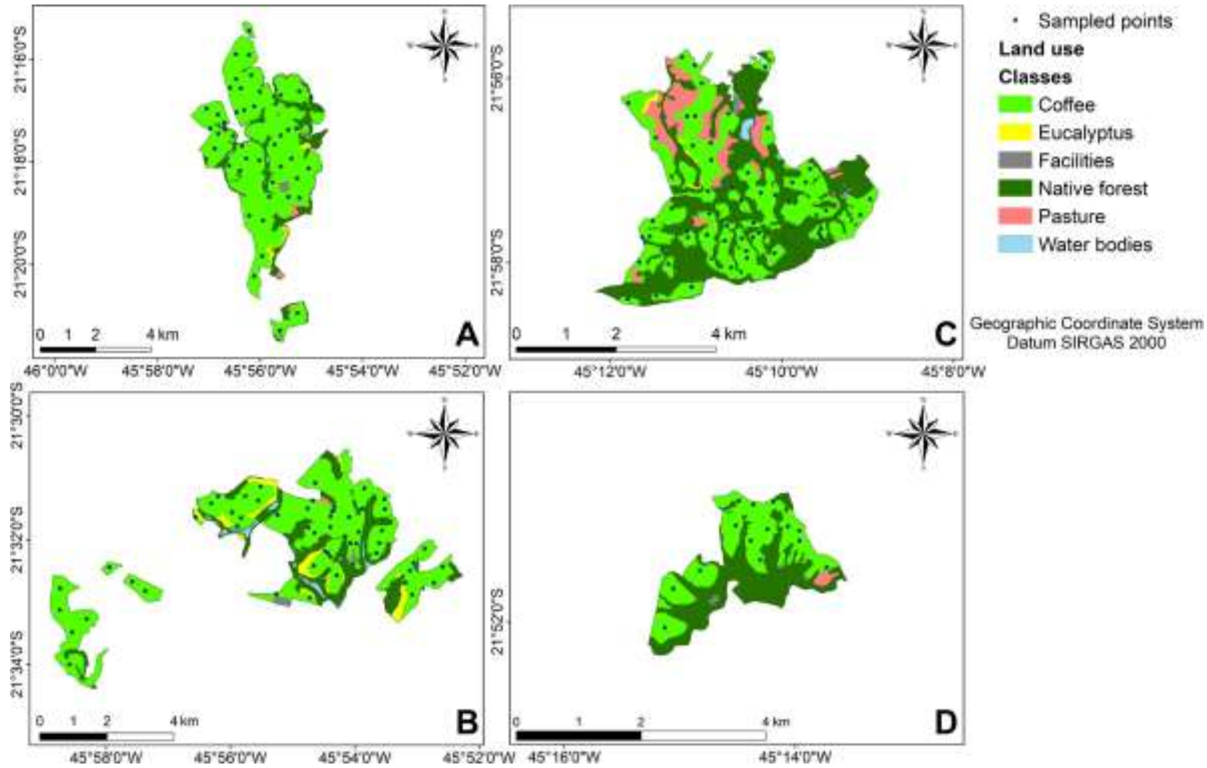

Figure 2. Mapping of land use; Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

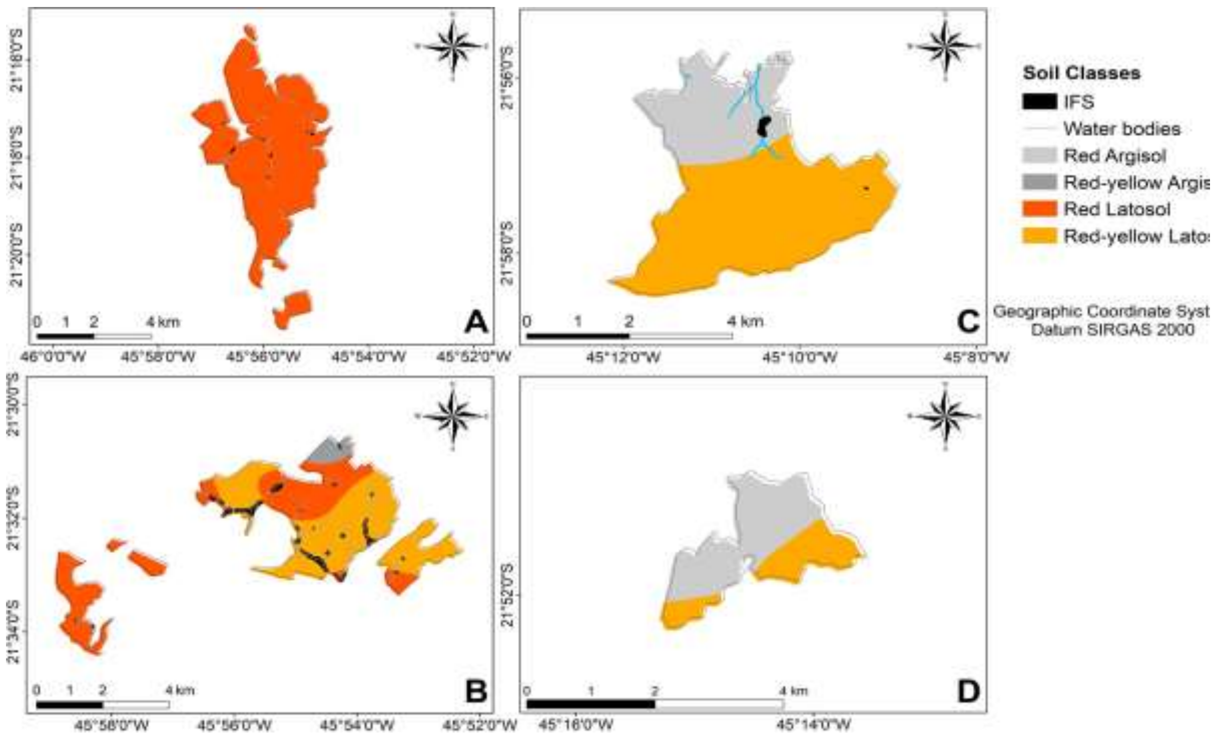

Figure 3. Mapping of soil classes; Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

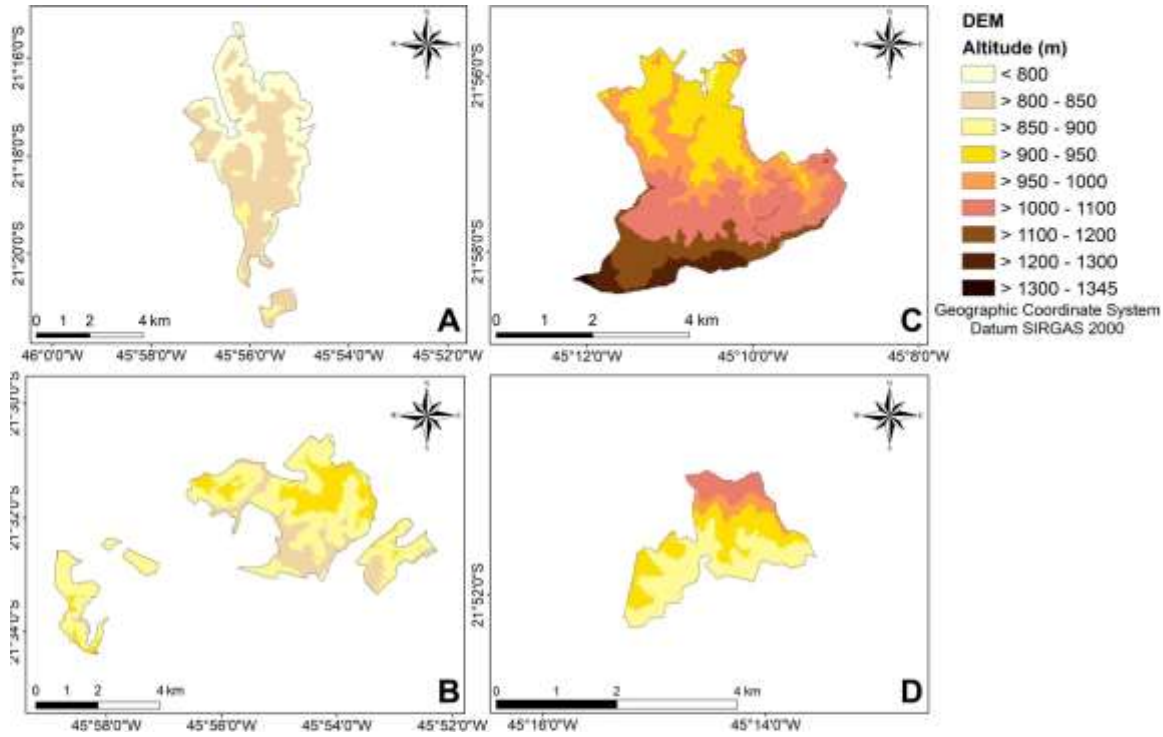

Figure 4. Mapping of digital elevation model; Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

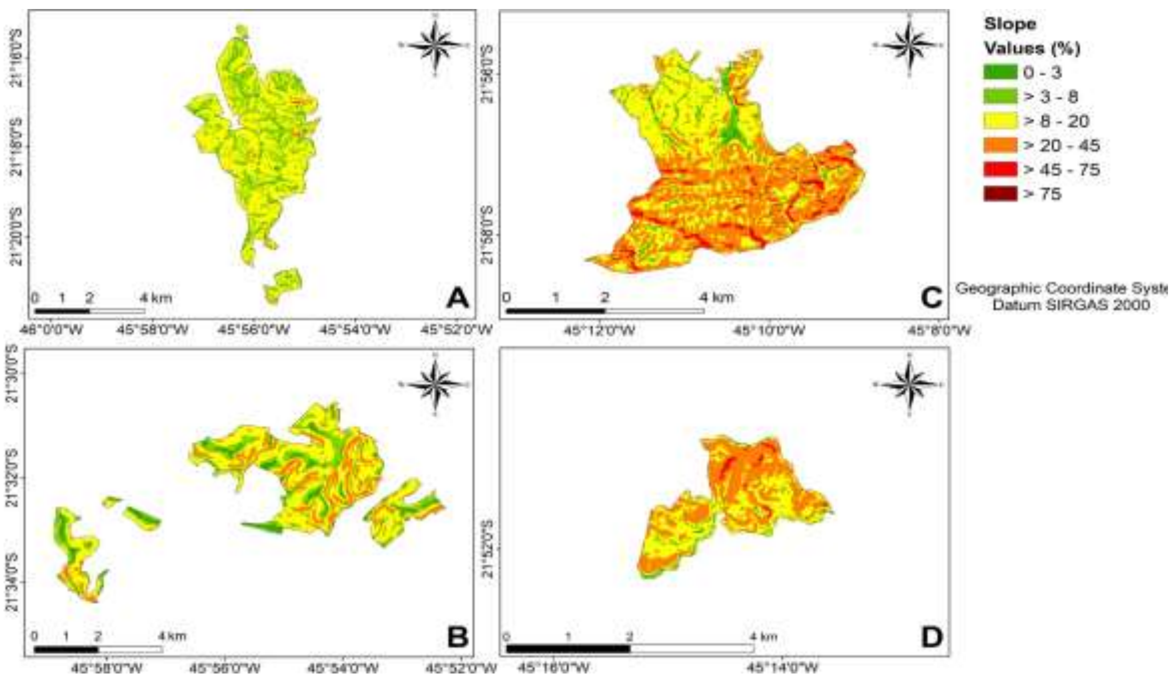

Figure 5. Mapping of slope; Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

The R factor was acquired from Souza *et al.* (2022), the K factor for Latosols from Lense *et al.* (2020a) and the K factor for Argisols from Marques *et al.* (1997). The researchers disregarded K for the IFS because it is a sediment deposition area.

The LS factor was estimated from the DEM, according to the equation proposed by Moore and Burch (1986), using the Raster Calculator tool (Equation 2):

$$LS = \{\frac{(FA \times ResDEM)}{22.13}\}^{0.4} \times \{\frac{(\sin S)}{0.0896}\}^{1.3}, \quad (2)$$

$$SDR = 0.472 \times A^{-0.125}$$

where LS is a topographic factor (dimensionless); FA is the flow accumulation, which represents the upstream contributing area accumulated for a cell; sin S is the sine of the slope area (degrees); and ResDEM is the spatial resolution of the DEM (meters).

The values of C and P were adapted from the specialized literature (Table 1). The values range from 0 to 1 and indicate higher erosive potential as they approach 1.

The RUSLE factors were changed to raster files and multiplied in the Raster Calculator tab, which resulted in the spatial distribution of soil losses.

The RUSLE results were validated by integrating this model with the sediment delivery rate (SDR), which represents the ratio between total erosion and sediment that reaches water bodies (Ebrahimzadeh *et al.*, 2018); the SDR was monitored at hydro-sedimentological stations of the Minas Gerais Institute for Water Resources Management (IGAM), located in Alfenas and Cambuquira, according to Batista *et al.* (2017). The SDR was estimated using Equation 3 of Vanoni (1975):

$$SDR = 0.472 \times A^{-0.125} \quad (3)$$

where SDR is the sediment delivery rate (%) and A is the watershed area (km^2).

2.4 Soil organic carbon (SOC) losses

Unlike soil losses, which were calculated for all land uses, the SOC loss rates were calculated based on the SOM contents exclusively under coffee crops. The soil was sampled at a depth of 0 to 20 cm by Ipanema Coffees and analyzed by Cooperativa Cooxupé, which calculated SOM contents, according to EMBRAPA (2017), in January 2023 (Supplementary document). We performed spatial distribution by kriging interpolation using the Geostatistical Wizard tool (Chen *et al.*, 2019).

SOC concentrations were calculated according to the USDA and NRCS (1996) by multiplying the SOM by Van Bemmelen's constant of 0.58 (Van Bemmelen, 1890). We then calculated the SOC losses by water erosion (Starr et al., 2000) by multiplying the SOM values by the soil losses in the Raster Calculator tool.

3. Results and discussion

3.1 Revised Universal Soil Loss Equation (RUSLE)

Table 2 presents the RUSLE results.

The R factor varied between 7070 and 7390 $MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1}$ (Table 2) and was thus classified as strong erosivity (Mello *et al.*, 2013). The K factor was classified as medium, with values ranged from 0.015 to 0.030 $Mg\ h\ MJ^{-1}\ mm^{-1}$, due to the predominance of Latosols, which have a low natural susceptibility to water erosion as a result of their textural and permeability characteristics (Bertol and Almeida, 2000; Mannigel *et al.*, 2002). As the areas have high erosivity rates, proper land use planning and priority adoption of conservation practices are required (Zanchin *et al.*, 2021, Lense *et al.*, 2022).

The highest mean LS factor was observed at Pinheirinho farm (Table 2). The highest LS values are associated with the highest slopes, more susceptible to water erosion. The Capoerinha and Rio Verde farms too have steep slopes, which indicate the need for water erosion mitigation.

Due to high R values, land use and management (factor C) and conservation practices (factor P) play key roles in controlling soil losses in places most vulnerable to water erosion; this is because lower C values result in higher plant density and lower water erosion rates (Renard *et al.*, 1997). Alternative soil management strategies can also reduce soil and SOC losses. Examples are the addition of sewage sludge in maize cultivation (Moreira *et al.*, 2020), and farmyard manure and green manure in sesame cultivation (Jalilian *et al.*, 2022), which contribute

Table 1. C and P factor values.

Land use	C factor	Source C factor	P factor*
Water bodies	-	-	-
Facilities	-	-	-
Coffee	0.086	Prochnow *et al.* (2005)	0.350
Eucalyptus	0.121	Silva *et al.* (2016)	0.560
Native forest	0.015	Silva *et al.* (2016)	0.200
Pasture	0.061	Galdino *et al.* (2015)	0.350

* Senanayake *et al.* (2022).

Table 2. Mean values of rainfall erosivity (R), soil erodibility (K), topographic (LS), land use and management (C), and conservation practices (P) factors; total and average soil loss rates, sediment delivery rate (SDR), estimated and observed sediment by areas.

RUSLE factors and SDR	Conquista	Capoeirinha	Rio Verde	Pinheirinho
$R(MJ\ mm\ ha^{-1}\ h^{-1}\ year^{-1})$	7070	7099	7200	7390
$K(Mg\ h\ MJ^{-1}\ mm^{-1})$	0.020	0.020	0.022	0.024
LS (dimensionless)	1.80	3.60	4.00	5.30
C (dimensionless)	0.074	0.068	0.051	0.049
P (dimensionless)	0.032	0.031	0.280	0.270
Total soil losses ($Mg\ year^{-1}$)	12,945	20,807	19,662	5736
Average soil losses ($Mg\ ha^{-1}\ year^{-1}$)	6.20	11.40	13.4	17.2
SDR (%)	32.1%	32.6%	32.5%	40.6%
Estimated SDR ($Mg\ ha^{-1}\ year^{-1}$)	2.0	3.7	4.3	6.9
Observed SDR ($Mg\ ha^{-1}\ year^{-1}$)	2.7	3.04	1.16	1.22

to improving the physicochemical properties of soils and agricultural production.

The lowest C values were obtained on the Pinheirinho farm (Table 2), which is composed almost entirely of native forest and coffee. On the Rio Verde and Pinheirinho farms, the smaller spacing between planting lines provides a higher density of plants per hectare, which generates higher levels of SOM, increases the water infiltration rate and reduces runoff. Manual harvesting was higher on these two farms, which reduces soil compaction by agricultural machinery. Regarding the P factor, in all productive areas, the planting of coffee was associated with conservation practices such as level planting, the construction of drainage terraces and the presence of infiltration basins.

The annual total soil losses were approximately 60 thousand tons on all four farms. The highest average soil losses were observed on the Pinheirinho, Rio Verde and Capoeirinha farms due to the higher slopes (Table 2). The results were close to those of Lense *et al.* (2020b), with an average soil loss of 19.0 $Mg\ ha^{-1}\ year^{-1}$. In Conquista, was estimated an mean soil loss of 6.2 $Mg\ ha^{-1}\ year^{-1}$ due to the lower slope (Figures 6a–6d).

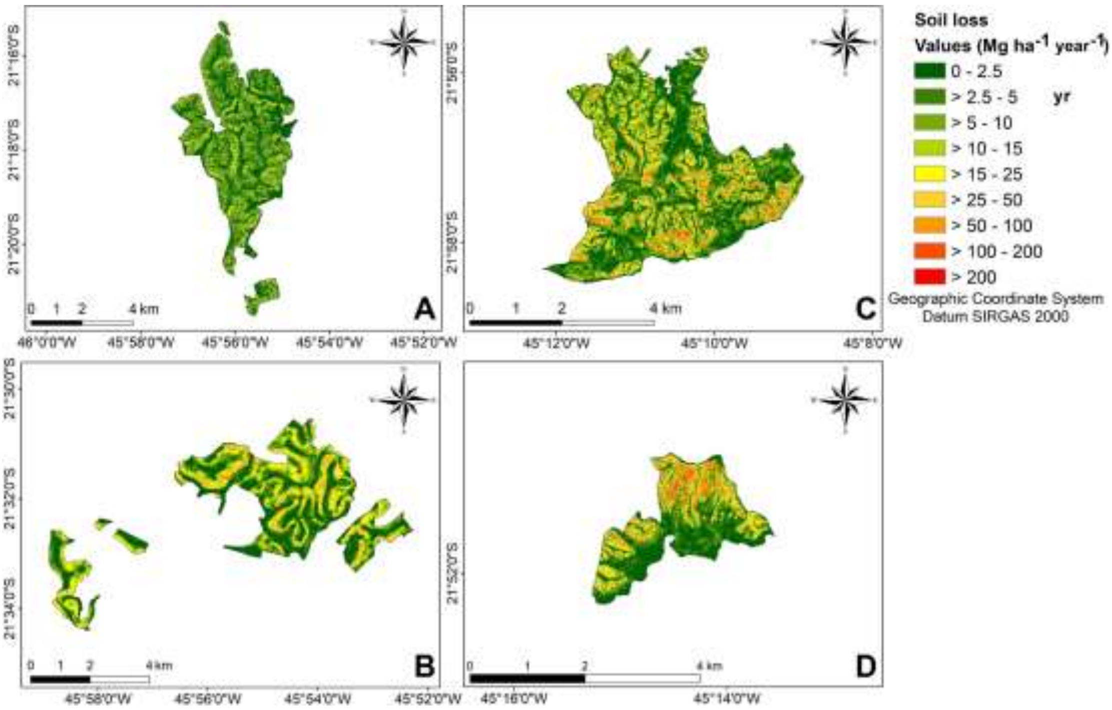

Figure 6. Spatialization of soil losses from Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

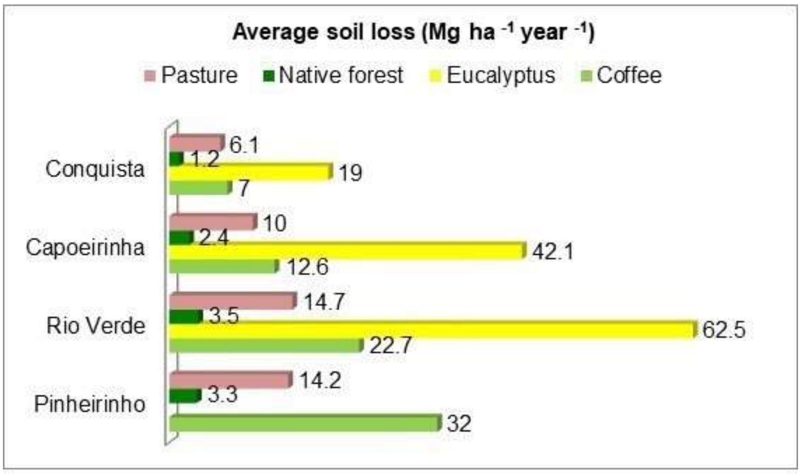

Figure 7. Average soil loss(Mg ha^{-1} year^{-1}) according to land use classes.

The SDR ranged from 32.1% to 40.6%, with an average of 34.45%. The areas with a higher SDR also had higher LS and C values (Table 1), which highlights the greater gravitational potential that favors the acceleration of runoff and hydrosedimentological flow and the intensification of water erosion in these areas.

The comparison of the estimated and observed SDRs (Table 2) showed that on the Conquista and Capoeirinha farms, the results were close, with errors of 26% and 22%, respectively. However, on the Rio Verde and Pinheirinho farms, the variation was high (Table 2), which could be explained by the greater slope, since the RUSLE tends to overestimate soil erosion on high-slope terrain (Nearing, 1998; Bircher *et al.*, 2022). Nevertheless, the lowest errors were associated with the highestsoil loss estimates (Amorim *et al.*, 2010). However, Bircher *et al.* (2022) consider that overestimated results are better than underestimated ones, especially when assessing environmental risks. Notably, all modelling is prone to inaccuracies. However, the application of a model must be understood with all the interrelationships of a given process, such as water erosion (Alewell *et al.*, 2019). Estimating soil losses on farms is an important tool to evaluate the dimensions of the erosion process and to identify priority areas for the adoption of conservation practices (Amorim *et al.*, 2010).

Figure 7 illustrates the average soil loss rates according to land use.

The highest average soil loss rates occurred in eucalyptus areas, with values between 19 and 62.50 Mg ha^{-1} year^{-1} . Such areas create shades by the canopy of the plants, which, associated with litter, make it difficult to plant other species, reduce soil aggregation and structuring and can even harm agricultural production in the surrounding areas (Latini *et al.*, 2020; Desta *et al.*, 2023). Eucalyptus is planted downhill on farms, with a spacing of up to 2 m between plants in steep areas. In addition, the eucalyptus cycle, which is approximately 6 years, as a source of energy biomass that can be used for drying coffee, tends to leave the soil exposed for long periods at the beginning of planting compared to coffee, though there are plants up to 45 years old in the area.

Soil losses in coffee ranged from 7 to 32 Mg ha^{-1} year^{-1} . The values were similar to those of Cerretelli *et al.* (2023), who estimated losses of 20.8 Mg ha^{-1} year^{-1} in Costa Rica and 7 Mg ha^{-1} year^{-1} in Guatemala in agroforestry systems. Therefore, the similarities between the results obtained in Central America and the study area reveal the effectiveness of the different management strategies adopted. In the case of farms, these practices ensure better protection of the soil against rainfall and favor the stability of soil aggregates due to (i) vegetation in coffee growing; (ii) planting on contour lines; (iii) infiltration basins; (iv) the use of manual harvesting in steep areas; (v) incorporation of plant residues into the soil; and (vi) organic fertilization (Didoné *et al.*, 2019; Alele *et al.*, 2023).

The lowest average soil loss was found in the native forest (Figure 6) due to (i) vegetation hindering the release of soil particles by runoff (Alele *et al.*, 2023); (ii) vegetation protects the supply of environmental and ecosystem services; (iii) increased soil moisture; and (iv) increased pollination, increasing productivity gains (Roubik, 2002; Latini *et al.*, 2020).

3.2 Soil organic matter (SOM) content

Contrary to expectations, the SOM content ranged from 1.5% to 4.4%. The lowest values were obtained in the flat and lower altitude areas of Conquista, and the highest were obtained in greater altitudes in Rio Verde (Figures 8a–8d).

Research presents conflicting information regarding the change in SOM content with altitude. Some indicate an increase in SOM at lower altitudes (Jeyakumar *et al.*,

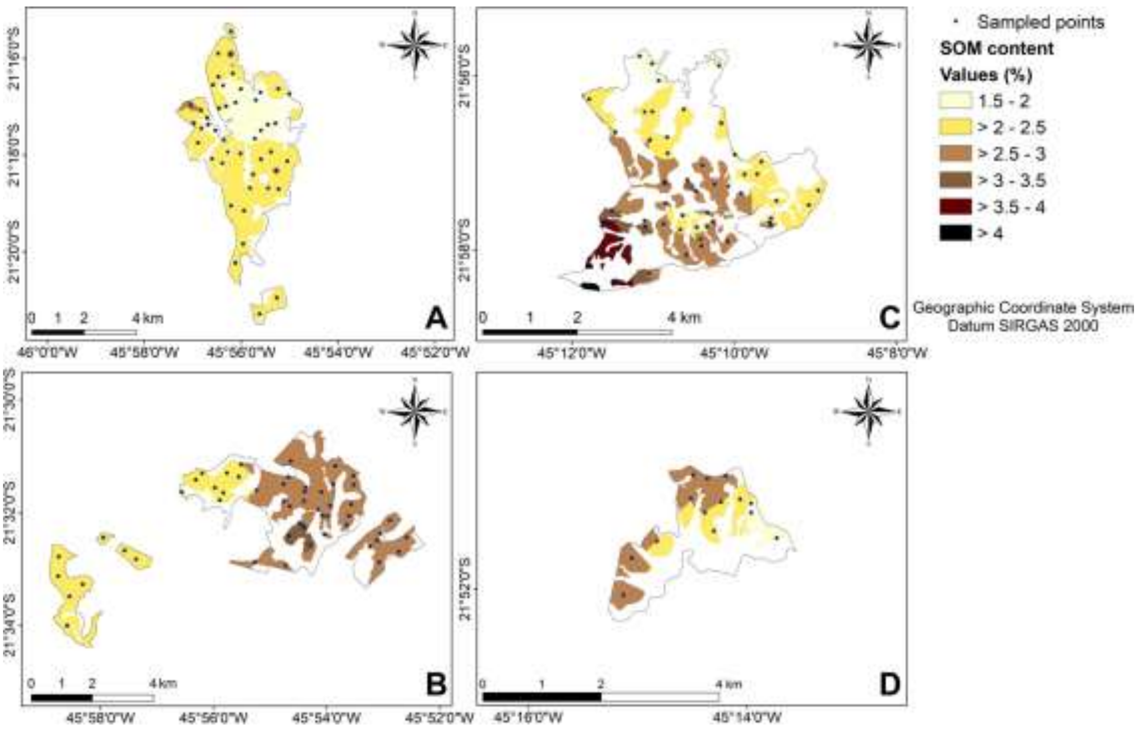

Figure 8. Spatial distribution of SOM content on Conquista (a), Capoeirinha (b), Rio Verde (c) and Pinheirinho (d) farms.

2020), while others indicate a decrease (He *et al.*, 2023). This variation can be explained by climatic zones (Li *et al.*, 2022; Yin *et al.*, 2022). In tropical zones, SOM contents increase with altitude; in temperate regions, they decrease (Sundqvist *et al.*, 2013). According to Yin *et al.* (2022), in tropical regions, high altitudes have lower temperatures, which slow decomposition and increase SOM levels and in temperate regions with higher altitudes, there is less plant biomass and consequently lower SOM.

There are higher levels of SOM due to manual harvesting in the higher altitudes and slopes of the Rio Verde and Capoeirinha farms, which incorporates a large amount of plant residues into the soil. In these areas, there is also a denser distribution of coffee plants, with smaller spacing, which provides a greater amount of SOM (Liu *et al.*, 2021). In this scenario, the main indicator affecting the SOM content was agricultural management, as highlighted by Angeletti *et al.* (2021).

On the Conquista farm, although the climate is warmer and has lower rainfall, there is greater runoff due to the presence of streets and the wider spacing between plants. The crops are more spaced and less densely planted; therefore, there is a greater incidence of solar radiation on the soil, which reduces moisture and the incorporation of C. In addition, mechanized harvesting and sweeping management, which removes coffee that falls on the ground, removes plant residues and prevents their incorporation in the environment. Pinheirinho, with lower temperatures and higher precipitation, has lower SOM contents due to its lower altitude, similar to the Jinghe River Basin on the Chinese Loess Plateau (Zhao *et al.*, 2021).

3.3 Soil organic carbon (SOC) losses

As expected, higher rates of SOC loss were associated with higher soil losses (Li *et al.*, 2016; Imamoglu and Dengiz, 2017) (Figures 9a–9d).

The areas with the highest susceptibility to SOM loss and C emission from the soil occurred in Rio Verde and Pinheirinho farms while Conquista and Capoeirinha had the lowest susceptibility. These deleterious impacts showed similar patterns to water erosion, resulting from topography and erosivity. However, the management practices adopted also affect the intensity of water erosion.

In this context, eucalyptus areas were subject to more intense deleterious effects than coffee areas. Despite the variable soil loss rates, it is worth noting that there is no safe level of soil loss (Mendes Júnior *et al.*, 2018), as the sustainability of agricultural systems demands the reduction of erosion rates to values close to zero (FAO and ITPS, 2015).

The spatialization of soil and SOC losses were similar to the results of Lense *et al.* (2019; 2020c) and Lense *et al.* (2022), who used the Erosion Potential Method (EPM)

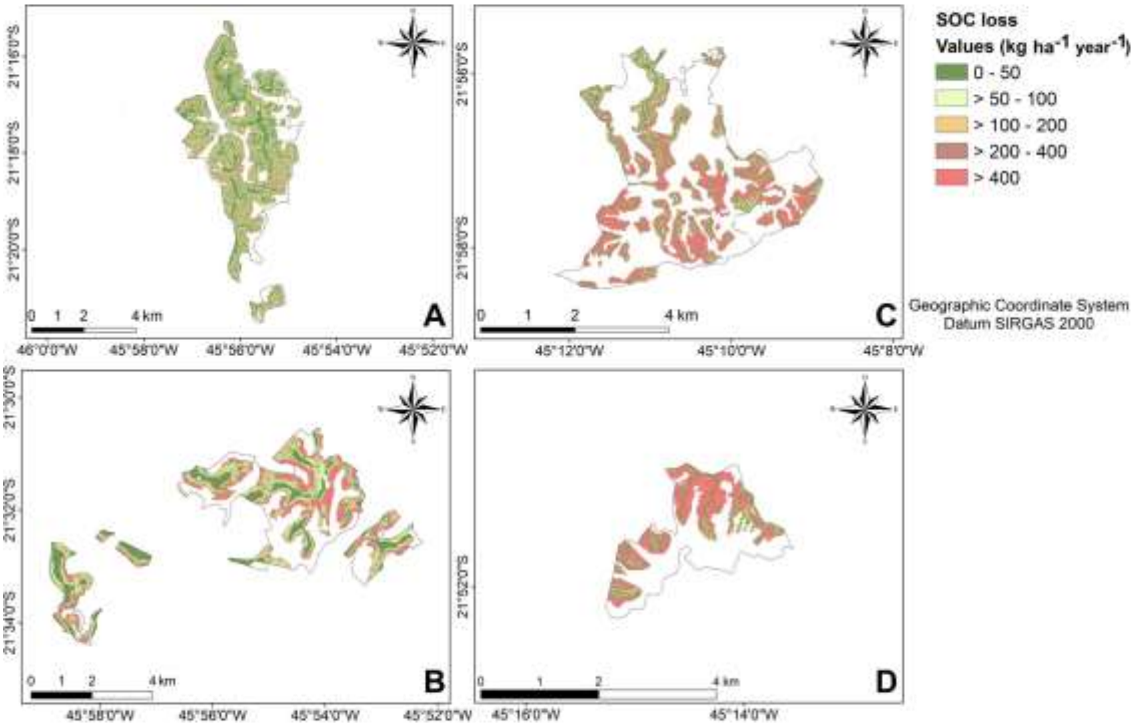

Figure 9. Spatial distribution of SOC losses in Conquista (a), Capoeirinha (b), Rio Verde (c), and Pinheirinho (d) farms.

(Gavrilovic, 1962), even when considering that EPM tends to underestimate such losses, unlike the RUSLE (Dragičević *et al.*, 2016; Chalise *et al.*, 2019; Lense *et al.*, 2020a).

In Capoeirinha, the mean soil loss for coffee plantation was 12.60 $Mg\ ha^{-1}\ year^{-1}$, higher than the previously reported values of 1.58 and 2.12 $Mg\ ha^{-1}\ year^{-1}$ (Mendes Júnior *et al.*, 2018; Lense *et al.*, 2019). These authors classified access roads and streets as exposed soil. Regarding the average SOC losses, the values were similar to the agricultural areas in Italy, Spain, and Romania, with values between 50 and 450 kg (Lugato *et al.*, 2016).

The average SOC loss is shown in Figure 10.

The adoption of sustainable management practices can mitigate soil, nutrient, and SOC losses through water erosion. The study areas have already adopted measures to improve soil aggregation and SOC fixation by reducing runoff. The vegetation cover in coffee streets improves soil structure, increases water retention capacity, and reduces the requirement for fertilizers and pesticides, all of which benefit the environment. This set of actions, combined with technologies in the field, increases productivity and reduces costs due to water erosion (Ayer *et al.*, 2015); furthermore, this approach can help maintain and open new C credit markets (Caramori *et al.*, 2020; Guimarães *et al.*, 2021).

SOC sequestration reduces GHG emissions. According to Hergoualc'h *et al.* (2012), a full sun coffee growing system stores an average carbon amount of 10.38$Mg\ C\ ha^{-1}$, while the system afforested with *Inga densiflora*, a fruit tree species widely grown in Central America, stores an average of 12.55 $Mg\ C\ ha^{-1}$. In addition to positive climatic effects, such management reduces temperatures, which delays fruit ripening and generates larger grains of better quality (Muschler, 2001). In addition, the forests surrounding coffee plantations favor the presence of birds and insects, which contribute to pollination and plague control (Chain-Guadarrama *et al.*, 2019). This type of management is an alternative method for the study area and is intended to reduce susceptibility to water erosion and increase carbon sequestration.

4. Conclusion

1. Average soil losses in coffee production ranged from 6.2 to 17.2 $Mg\ ha^{-1}\ year^{-1}$, with higher rates on the steeper slopes. The values indicate that conservation management is mainly responsible for reducing soil losses and mitigating the impacts associated with water erosion.

2. SOC levels in coffee growing varied because of agricultural management, with higher values associated with higher altitudes in fields with denser coffee plants and manual harvesting.

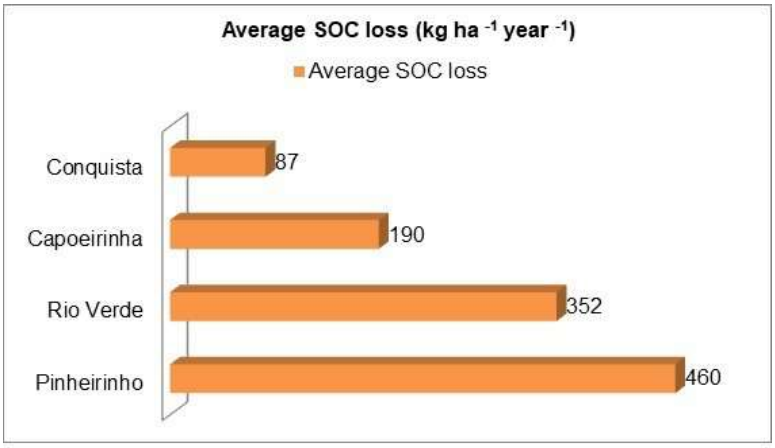

Figure 10. Average SOC loss (kg ha^{-1} year^{-1}) in coffee growing areas.

3. SOC losses ranged from 1 to 6600kg ha^{-1} year^{-1}, with high rates on the highest slopes. The methodological procedures were successful in spatializing the areas with the highest SOC losses. The use of conservation management favors SOC stocks and reduces the impacts of coffee growing on climate change.

4. The use of environmental modelling and remote sensing technologies is a fast and efficient tool to monitor the water erosion processes, soil, nutrient, and SOC losses under spatiotemporal variations.

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Supplementary document

FID (for ArcGIS)	Sequence number	Latitude	Longitude	Gleb coffee identification	Soil organic matter (%)	Soil organic carbon (%)
0	1	-45,93690109	-21,25740051	A1	2,90	1,68
109	2	-45,24700165	-21,85930061	A10	2,70	1,57
23	3	-45,93989944	-21,30279922	A12	3,10	1,80
27	4	-45,93270111	-21,33069992	A15	2,90	1,68
25	5	-45,93030167	-21,31139946	A16	2,80	1,62
29	6	-45,9292984	-21,30660057	A17	2,40	1,39
36	7	-45,92660141	-21,30150032	A18	2,30	1,33
2	8	-45,93690109	-21,26519966	A2	2,90	1,68
31	9	-45,92409897	-21,31139946	A20	2,60	1,51
32	10	-45,92050171	-21,31170082	A21	2,60	1,51
138	11	-45,18500137	-21,94020081	A22	2,40	1,39
133	12	-45.193677	-21.941174	A24	2,60	1,51
164	13	-45,16460037	-21,95219994	A25	3,50	2,03
6	14	-45,9396019	-21,27599907	A28	2,70	1,57
34	15	-45,91749954	-21,30209923	A29	2,50	1,45
3	16	-45,93619919	-21,27179909	A3	2,80	1,62
114	17	-45,23730087	-21,85339928	A31	3,10	1,80
117	18	-45,2344017	-21,85289955	A32	3,40	1,97
159	19	-45,17070007	-21,95409966	A33	2,90	1,68
130	20	-45,19169998	-21,95919991	A35	2,50	1,45
40	21	-45,92419815	-21,28949928	A36	1,90	1,10
77	22	-45,90650177	-21,52709961	A37	4,00	2,32
78	23	-45,90660095	-21,5298996	A38	3,20	1,86
79	24	-45,91080093	-21,53149986	A39	2,70	1,57
7	25	-45,93349838	-21,2772007	A4	2,60	1,51
43	26	-45,17440033	-21,96240044	A40	2,60	1,51
151	27	-45,92060089	-21,27709961	A40	2,90	1,68
167	28	-45,16529846	-21,95590019	A41	3,00	1,74
51	29	-45,97230148	-21,55290031	A41	2,30	1,33
41	30	-45,97829819	-21,55540085	A42	1,80	1,04
49	31	-45,92160034	-21,28910065	A42	2,70	1,57
9	32	-45,93849945	-21,28310013	A46	2,80	1,62
45	33	-45,18489838	-21,96220016	A48	2,20	1,28
100	34	-45,88119888	-21,53569984	A48	3,00	1,74
129	35	-45,91680145	-21,27890015	A48	3,10	1,80
19	36	-45,17449951	-21,95549965	A49	2,40	1,39
156	37	-45,93920135	-21,2947998	A49	2,70	1,57
1	38	-45,94129944	-21,26490021	A5	3,10	1,80
153	39	-45,17100143	-21,96139908	A50	3,30	1,91
105	40	-45,17620087	-21,95330048	A51	1,90	1,10
157	41	-45,87639999	-21,54059982	A51	2,70	1,57
97	42	-45,89339828	-21,53429985	A53	2,10	1,22
62	43	-45,95529938	-21,54780006	A55	2,60	1,51
61	44	-45,95819855	-21,54450035	A56	2,50	1,45
73	45	-45,91260147	-21,52490044	A57	2,80	1,62
46	46	-45,97999954	-21,54759979	A58	2,20	1,28
66	47	-45,1731987	-21,95050049	A61	2,00	1,16
158	48	-45,93289948	-21,52599907	A61	3,70	2,15
70	49	-45,16650009	-21,94849968	A62	2,00	1,16
163	50	-45,9292984	-21,52160072	A62	3,50	2,03
143	51	-45,18030167	-21,94820023	A7	2,70	1,57
136	52	-45,18349838	-21,93099976	A74	2,80	1,62
21	53	-45,25090027	-21,86190033	A9	2,50	1,45
108	54	-45,93790054	-21,2989006	A9	2,80	1,62
33	55	-45.922198	-21.315642	AR1	2,90	1,68
30	56	-45.7925975	-21.313495	AR2	2,90	1,68
142	57	-45,18389893	-21,94560051	B1	3,00	1,74
104	58	-45,2397995	-21,85499954	B11	2,90	1,68
115	59	-45,87870026	-21,54490089	B11	3,10	1,80
110	60	-45,24150085	-21,8491993	B12	3,30	1,91
92	61	-45,89799881	-21,52499962	B19	3,30	1,91
85	62	-45,90480042	-21,54290009	B20	2,20	1,28
81	63	-45,90790176	-21,53639984	B21	2,30	1,33
71	64	-45,92520142	-21,51910019	B22	2,00	1,16
123	65	-45,19430161	-21,96660042	B23	3,00	1,74
91	66	-45,9015007	-21,5272007	B27	4,40	2,55
93	67	-45,8973999	-21,51959991	B28	3,20	1,86
96	68	-45,8927002	-21,53089905	B29	2,50	1,45
82	69	-45,1833992	-21,94020081	B3	3,10	1,80
139	70	-45,90719986	-21,53689957	B3	2,90	1,68
99	71	-45,8852005	-21,54170036	B30	2,60	1,51
124	72	-45,1841011	-21,97120094	B34	3,10	1,80
131	73	-45,18500137	-21,96109962	B36	2,60	1,51
152	74	-45,17219925	-21,96220016	B42	2,40	1,39
150	75	-45,17720032	-21,96010017	B5	2,50	1,45
144	76	-45,18099976	-21,9538002	B64	2,70	1,57
122	77	-45,19100189	-21,97270012	B65	3,40	1,97
84	78	-45,16799927	-21,96509933	B66	2,20	1,28
154	79	-45,9109993	-21,54030037	B66	3,50	2,03
145	80	-45,18069839	-21,95779991	B67	3,80	2,20
126	81	-45,18980026	-21,96450043	B68	4,20	2,44
125	82	-45,18870163	-21,96699905	B69	3,10	1,80
149	83	-45,17770004	-21,96279907	B70	3,50	2,03
128	84	-45,19369888	-21,96209908	B71	2,30	1,33
121	85	-45,19649887	-21,97330093	B73	4,40	2,55
60	86	-45,96590042	-21,54000092	B75	2,50	1,45
69	87	-45,92589951	-21,52280045	B77	2,40	1,39
72	88	-45,92070007	-21,52669907	B78	2,20	1,28
146	89	-45,18119812	-21,96170044	C14	2,50	1,45
160	90	-45,16790009	-21,9545002	C16	2,20	1,28
147	91	-45,17340088	-21,96590042	C26	3,00	1,74
148	92	-45,17649841	-21,96769905	C27	3,00	1,74
113	93	-45,23649979	-21,84939957	C28	3,70	2,15
112	94	-45,23939896	-21,84980011	C29	4,00	2,32
111	95	-45,2419014	-21,85280037	C30	4,20	2,44
89	96	-45,90259933	-21,53240013	C31	3,80	2,20
35	97	-45,92129898	-21,30529976	C33	2,30	1,33
127	98	-45,19219971	-21,96199989	C38	2,90	1,68
155	99	-45,17350006	-21,9647007	C39	3,80	2,20
141	100	-45,18040085	-21,94510078	C46	2,40	1,39
119	101	-45,23270035	-21,85359955	C52	2,90	1,68
140	102	-45,17699814	-21,93969917	C56	2,30	1,33
98	103	-45,89410019	-21,53689957	C6	2,30	1,33
171	104	-45,15909958	-21,96220016	C80	3,60	2,09

170	105	-45,15940094	-21,96150017	C81	3,00	1,74
169	106	-45,15909958	-21,96069908	C82	2,90	1,68
168	107	-45,15800095	-21,95730019	C83	2,90	1,68
5	108	-45,94120026	-21,2730999	I30	3,40	1,97
4	109	-45,90650177	-21,53790092	I32	2,90	1,68
83	110	-45,94309998	-21,2758007	I32	2,60	1,51
52	111	-45,97439957	-21,55470085	I33	2,10	1,22
88	112	-45,90110016	-21,53420067	I45	2,00	1,16
135	113	-45,18600082	-21,92959976	I58	2,40	1,39
137	114	-45,18209839	-21,93429947	I59	2,50	1,45
63	115	-45,16930008	-21,94239998	I63	2,40	1,39
162	116	-45,93849945	-21,52359962	I63	2,90	1,68
74	117	-45,91120148	-21,52280045	I64	2,30	1,33
80	118	-45,91249847	-21,53000069	I65	2,60	1,51
67	119	-45,93040085	-21,52750015	I67	2,60	1,51
68	120	-45,9314003	-21,52969933	I69	2,70	1,57
90	121	-45,89889908	-21,53129959	I79	2,30	1,33
106	122	-45,92100143	-21,54809952	I83	2,30	1,33
161	123	-45,17210007	-21,95960045	L13	2,20	1,28
95	124	-45,89199829	-21,52510071	L25	2,70	1,57
65	125	-45,93659973	-21,52169991	L26	2,00	1,16
16	126	-45,94689941	-21,29080009	L44	2,40	1,39
15	127	-45,94469833	-21,28949928	L45	1,80	1,04
59	128	-45,96870041	-21,56609917	M1	2,70	1,57
17	129	-45,91059875	-21,51810074	M10	2,60	1,51
75	130	-45,94820023	-21,29570007	M10	2,50	1,45
24	131	-45,89960098	-21,53440094	M13	2,50	1,45
87	132	-45,93690109	-21,31749916	M13	4,00	2,32
26	133	-45,93239975	-21,31909943	M14	2,30	1,33
103	134	-45,88460159	-21,54809952	M17	2,70	1,57
39	135	-45,92660141	-21,29140091	M19	2,00	1,16
13	136	-45,94960022	-21,28910065	M22	2,00	1,16
11	137	-45,94710159	-21,2845993	M23	2,30	1,33
12	138	-45,95080185	-21,28269958	M24	2,50	1,45
28	139	-45,93529892	-21,33720016	M25	2,30	1,33
134	140	-45,19100189	-21,94409943	M57	2,60	1,51
118	141	-45,23270035	-21,85499954	M8	2,50	1,45
165	142	-45,16109848	-21,94980049	M84	2,60	1,51
166	143	-45,16199875	-21,95219994	M85	2,10	1,22
102	144	-45,8871994	-21,54319954	P14	2,10	1,22
37	145	-45,92309952	-21,2989006	P34	2,30	1,33
101	146	-45,88410187	-21,53949928	P4	3,00	1,74
14	147	-45,94219971	-21,29150009	P41	2,60	1,51
18	148	-45,94509888	-21,28720093	P41	2,60	1,51
38	149	-45,92860031	-21,29430008	P43	2,90	1,68
8	150	-45,93529892	-21,28190041	P6	2,70	1,57
94	151	-45,89210129	-21,52249908	P68	2,40	1,39
22	152	-45,93360138	-21,29949951	P8	3,20	1,86
107	153	-45,91199875	-21,5489006	R24	2,70	1,57
42	154	-45,92829895	-21,28100014	R38	2,90	1,68
64	155	-45,94269943	-21,52729988	R74	2,50	1,45
20	156	-45,94340134	-21,30120087	S11	2,50	1,45
116	157	-45,23839951	-21,85779953	U20	3,20	1,86
132	158	-45,19639969	-21,93779945	U21	3,30	1,91
76	159	-45,90599823	-21,5258007	U23	3,00	1,74
10	160	-45,94100189	-21,28380013	U27	2,90	1,68
44	161	-45,92670059	-21,27829933	U47	2,10	1,22
86	162	-45,90050125	-21,53989983	U54	2,80	1,62
120	163	-45,22880173	-21,85890007	U55	2,60	1,51

4 PAPER II – Spatiotemporal Dynamics of Soil and Soil Organic Carbon Losses via Water Erosion in Coffee Cultivation in Tropical Regions

sustainability

MDPI

Article

Spatiotemporal Dynamics of Soil and Soil Organic Carbon Losses via Water Erosion in Coffee Cultivation in Tropical Regions

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Abstract: Water erosion has severe impacts on soil and the carbon cycle. In tropical regions, it is significantly influenced by rainfall, soil erodibility, rapid changes in land use and land cover (LULC), and agricultural management practices. Understanding the dynamics of water erosion is essential for implementing precise land degradation control. This study aimed to estimate soil and soil organic carbon (SOC) losses due to water erosion over five years in a coffee-producing area in Brazil using the revised universal soil loss equation (RUSLE). The results revealed that average soil losses in coffee plantation areas ranged from 1.77 to 1.80 Mg ha^{-1} yr^{-1}, classified as very low. Total and potential soil loss ranged from 2184.60 to 6657.14 Mg ha^{-1}, a 305% difference, demonstrating the efficiency of vegetative cover (C factor) and conservation practices (P factor) in reducing soil loss rates. SOC losses were less than 200 kg ha^{-1} yr^{-1}, with averages of 17.67 and 13.00 kg ha^{-1} yr^{-1} in coffee areas. In conclusion, agricultural management practices, such as the presence of native vegetation, maintaining vegetative cover in coffee rows, contour planting, and improving agronomic techniques, are essential for reducing soil and SOC losses, even in scenarios of biennial alternation in coffee production. Thus, sustainable agricultural management plays a crucial role in mitigating water erosion, maintaining productivity, and addressing climate change.

Keywords: RUSLE; InVEST; SOM; LULC; agricultural management

1. Introduction

The adverse impacts of soil degradation raise significant concerns. One-third of the world's soils are degraded by erosion [1]. There are estimated annual losses of 75 Pg on arable lands [2], leading to severe environmental and socioeconomic damages [3]. Approximately 80% of arable lands face moderate to severe erosion [4].

Erosion is a natural process but is exacerbated by anthropic activities, such as native forest conversion to arable lands and unsustainable agricultural management systems [5].

The primary consequence of water erosion is the loss of soil, soil organic carbon (SOC), soil organic matter (SOM), and the depletion of nutrients, phosphorus (P), and pesticides [6]. Water erosion also disrupts soil–atmosphere interactions, reduces agricultural produc- tivity, and causes sedimentation, eutrophication, and pollution of water bodies, thereby threatening global food and nutritional security [7].

In tropical areas, erosion is accelerated by intense rainfall [8], greater soil erodibility [9], and faster changes in land use and land cover (LULC) [10]. In Brazil, the annual soil losses in 2002 were estimated at 822.6 million Mg, with a cost of USD

6 billion [11]. In the same year, the costs associated with fertilizer losses range from USD 18.15 to USD 107.76 per hectare per year [12]. In the São Paulo state, the average estimated rate of soil loss is 30 Mg ha^{-1} yr^{-1} [8]. The cumulative effects over time lead to significant soil degradation and a loss of productivity [10].

Brazil holds the largest amount of cultivable land (around 850 million ha) and currently (2024) is the world's leading coffee producer [13] due to climatic conditions. There are approximately 330 thousand rural properties dedicated to coffee cultivation, 78% of which are family-owned farms where coffee serves as the primary source of income [14]. Despite its socioeconomic significance, much debate surrounds the environmental impacts of the coffee production model, which is historically based on the deforestation of the Atlantic Forest and the Cerrado, full-sun monoculture, and intensive soil use, and is adapted from sugarcane cultivation techniques [15]. These factors may aggravate the deleterious impacts of water erosion, particularly soil and SOC losses, increasing greenhouse gas emissions and depleting the soil's nutrient content and productive capacity [16]. Given this situation, adopting sustainable agricultural management is essential, especially in the Minas Gerais state, which is responsible for approximately 50% of Brazil's coffee production [14].

SOC is often used as a key indicator of soil quality because it reflects anthropic actions [17]. Essential elements in preserving and increasing SOC stocks include agricultural management practices and C input via fertilization [18]. These practices can enhance SOC reservoirs and mitigate deficits arising from water erosion [19]. Thus, the main source of SOC comes from SOM, which contains most of the essential nutrients, such as N and P [18]. Furthermore, increasing SOM and SOC levels in tropical agricultural lands would help achieve the goals of the "4/1000 Initiative: Soils for Food Security and Climate", an international initiative launched during COP21 in 2015, with the goal of increasing SOC by 0.4% per year, that is, 4 per thousand (4/1000), which aims to ensure that agriculture plays its part in combating climate change and food security by more than 40 countries [20]. However, there is a lack of research addressing the spatiotemporal dynamics of soil and SOC losses associated with LULC changes and agricultural management practices for tropical regions, especially given the context of climate change [21].

Estimating and spatializing soil and SOC losses is essential for long-term water erosion mitigation [22]. Mathematical models utilizing geographic information systems (GISs) are widely employed for water erosion assessment, offering alternatives to traditional empirical methods, which are labor-intensive, expensive, and require several years of analysis [23]. These models efficiently estimate soil and SOC losses and evaluate the sediment delivery ratio (SDR), such as the revised universal soil loss equation (RUSLE), which is applied worldwide [24,25]. It can be implemented in GIS softwares, such as ArcGIS 10.3 [26] and InVEST 3.13 (integrated valuation of ecosystem services and tradeoffs) [27]. This study aimed to estimate the spatial losses of soil and SOC in an area with different LULC types that are predominantly dedicated to coffee production in southeastern Brazil between 2017 and 2022. For this purpose, we utilized the RUSLE in ArcGIS and InVEST. The aim was to assess the temporal influence of LULC, LULC changes, and agricultural management practices on water erosion, analyze within the context of sustainable coffee production, and make comparisons with other areas.

2. Materials and Methods

2.1. Study Area and Description

The study area was the Conquista Farm, owned by Ipanema Coffees (Ipanema Agrícola S.A.), located in the Alfenas Municipality, Minas Gerais state, Brazil. The local climate is humid subtropical (Cwb), according to the Köppen classification [28], characterized by dry winters and mild summers, with an average annual temperature and precipitation of 21.2 °C and 1500–1750 mm, respectively. The geological substrate consists of gneisses, overlaid by quaternary soil coverings, comprising unconsolidated fluvial deposits of gravel, sand, and clay [29].

The area is characterized by Red Latosol [30], corresponding to Ferralsol in the World Reference Base for Soil Resources (WRB) [31], and, to a lesser extent, indiscriminate flood- plain soils (IFSs) in sediment deposition areas (Figure 1A). The Latosols of this area originate from crystalline rocks, such as granites and gneisses, commonly found in mountainous regions and/or plateaus. Their color is reddish-brown due to the higher iron content. The predominant texture is clayey, which provides good water and nutrient retention capacity. However, these soils exhibit low natural fertility due to intense leaching, meaning they lose many soluble nutrients through rainfall. The pH is often acidic, necessitating correction through the application of lime [30].

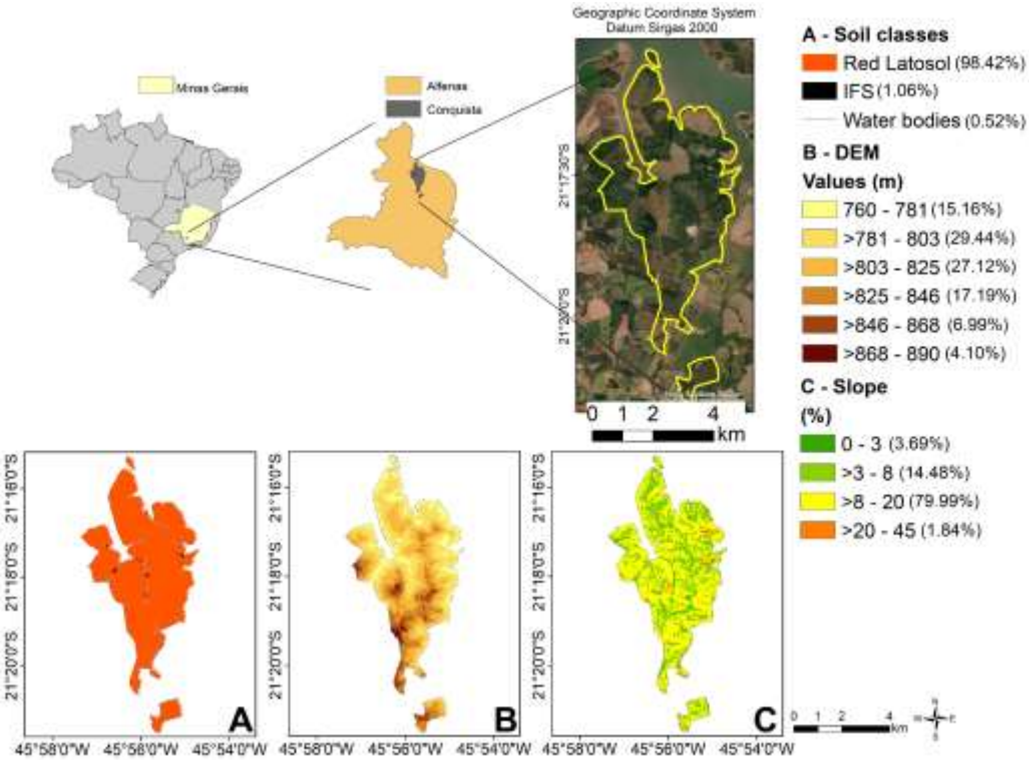


Figure 1. Conquista Farm location map. (**A**) Soil classes; (**B**) digital elevation model (DEM); (**C**) slope. IFS = indiscriminate floodplain soil.

The altitude ranges from 760 to 890 m, with an average slope ranging between 3 and 8%, suitable for coffee production (Figure 1B). The slope gradients range from flat (0–3%) to strongly undulating (>20–45%) (Figure 1C).

The Conquista Farm encompasses 2045.90 ha, with over 60% dedicated to coffee cultivation. Coffee plots range from 1.85 to 79.85 ha and are distributed according to the

variety, with Acaiá, Paraíso 2, and Mundo Novo predominating. The number of bags (bag = 60 kg) harvested varies from 22 to 95 per ha, with an average productivity of 45 per year with conventional tillage, monocultural systems, and a full-sun model. Several conservation practices are employed during production: (i) growing coffee seedlings in a vivarium; (ii) selecting the ideal seeds for planting based on the soil composition and topographical features; (iii) instituting a fertilization regime guided by annual soil and foliar analysis with continuous monitoring of weed, disease, and pest populations; (iv) integrating agronomic technological advances throughout the production process;
(v) using drip-irrigation systems; (vi) promoting vegetation cover between coffee rows, mainly Brachiaria species; (vii) using organic fertilizers with slow-release formulations;
(viii) preserving remnants of native vegetation and carrying out routine pruning; and (ix) harvesting coffee beans at the ideal stage of ripeness.

2.2. Methodology

To achieve our goals, we implemented a methodological approach in different time series, in 2017, 2019, and 2022, which (i) employed the RUSLE to estimate the soil and SOC losses; (ii) validated the soil loss data between the sediment yield observed and the SDR; and (iii) evaluated the changes in the SOM and SOC contents in coffee cultivation utilizing fieldwork collection samples covering depths from 0 to 20 cm, as shown in the flowchart in Figure 2. The choice of these years was due to a lack of information for some soil samples in 2021; therefore, 2022 was selected.

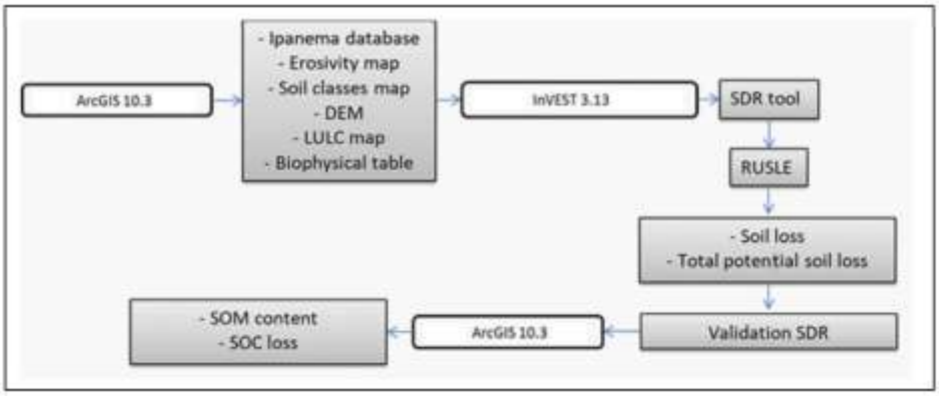


Figure 2. Flowchart of methodological procedures.

The SDR tool is part of the InVEST 3.13 software [27] and utilizes the RUSLE [24] to estimate the total and maximum soil losses coupled with other methodologies [32,33]. The RUSLE considers five multiplied parameters, as shown in Equation (1):

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the average annual soil loss (Mg ha^{-1} yr^{-1}); R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}); K is the soil erodibility factor (Mg h MJ^{-1} mm^{-1}); LS is the topographic factor expressing the relationship between the slope length (L) and slope (S) (dimensionless); C is the factor for land use and cover (dimensionless); and P is the factor for conservation practices (dimensionless).

We calculated the maximum soil loss, which is the potential total soil loss in the original land cover, with a lack of agricultural management practices via Equation (2) [27]:

$$A = R \times K \times LS \tag{2}$$

InVEST 3.13 requires specific input data to utilize the SDR tool. These data were initially generated in ArcGIS 10.3 [26] and included the DEM, erosivity, erodibility, land cover, biological data table (C and P factors), watershed area or specific area, threshold flow accumulation value, maximum SDR value, Borselli connectivity index (IC0 parameter), and maximum L value. The input data in the raster and vector formats represent quantitative maps with information correlating to the numerical values linked to each pixel.

We initially acquired the DEM from the L-band image of the Alos PALSAR satellite [34] at a resolution of 30 m, but it was resampled to 12.5 m. We obtained the erosivity factor (R) for the southern region of Minas Gerais [35]. Subsequently, we determined the erodibility factor (K) in two stages: Firstly, we generated a map of soil classes based on the soil map of Minas Gerais [36]. Secondly, we calculated the erodibility of Latosols [37], excluding areas of sedimentary deposits near bodies of water (30 m). Following this, we extracted the LULC data from MapBiomas Collection 8 of 2023 [38] for Alfenas in 2017, 2019, and 2022 (Figure 3A–C). These years were selected based on the availability of data from the farm. After this, we conducted field checks to mitigate errors associated with the LULC classification (Table 1).

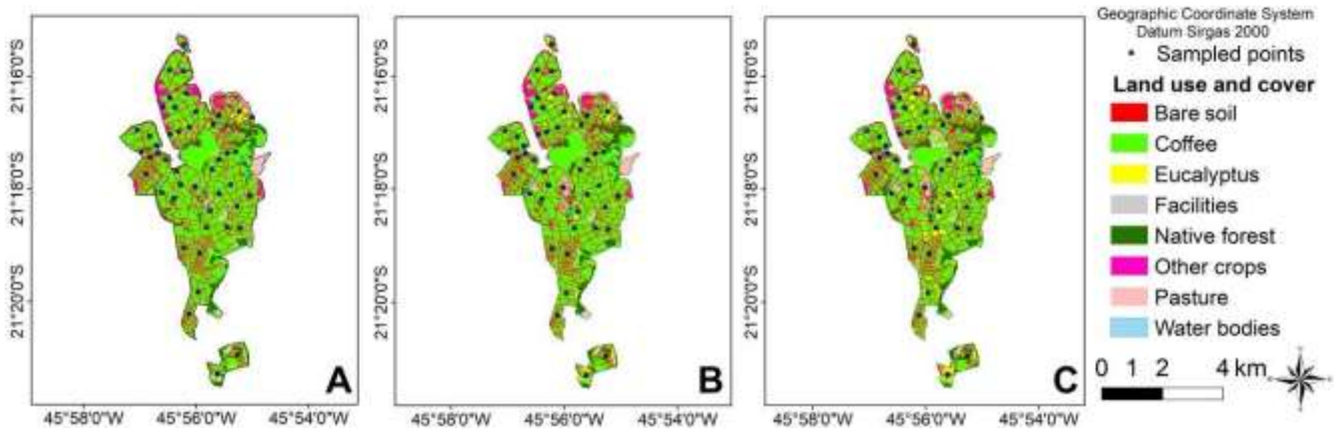


Figure 3. LULC maps and soil sampling of Conquista Farm for (**A**) 2017, (**B**) 2019, (**C**) 2022.

Table 1. LULC areas (ha) and percentage in 2017, 2019, and 2022.

Class	Year					
	2017		2019		2022	
	ha	%	ha	%	ha	%
Coffee	1325.94	64.81	1288.40	62.98	1234.24	60.33
Eucalyptus	24.23	1.19	40.08	1.96	61.98	3.03
Facilities	4.50	0.22	4.70	0.23	3.69	0.18
Native forest	135.93	6.64	151.41	7.40	170.36	8.33

* Other crops	84.93	4.15	85.82	4.19	83.66	4.09
Pasture	89.66	4.38	92.29	4.51	110.11	5.38
Water bodies	5.53	0.27	5.53	0.27	6.33	0.31
Bare soil	375.18	18.34	377.67	18.46	375.53	18.35
Total	2045.90	100	2045.90	100	2045.90	100

* Miscellany of agriculture and pasture.

The biological data table establishes the correlation between the LULC classes and the values of the C and P factors of the RUSLE. These factors represent the impact of land use and cover (C) and conservation practices (P) on water erosion. We obtained the C and P values from the specialized literature (Table 2).

Table 2. Correspondence of the C and P value factors and sources.

LULC	C Factor	Source C Factor	P Factor [39]
Coffee	0.086	[40]	0.350
Eucalyptus	0.121	[41]	0.560
Native forest	0.001	[42]	0.200
Other crops	0.096	[43]	0.350
Pasture	0.061	[44]	0.350
Bare soil	0.600 *	[45]	1.000

* For the bare soil, we adopted a C value of 0.6, according to the similarity with Ethiopia.

We used the following default values in InVEST: 1000 for the threshold flow accumu- lation parameter [27]; 2 and 0.5 for Borselli's K and IC0 parameters, respectively [32]; 0.8 for the maximum SDR value [33]; and 122 for the maximum L value [24,46]. Consequently, we generated maps representing the total and maximum soil losses as the LULC for 2017, 2019, and 2022.

2.3. *Sediment Delivery Ratio (SDR)*

We examined the correlation between the actual sediment yield and the estimated SDR to validate the soil loss using the RUSLE. The sediment yield represents the total eroded soil generated in a watershed, while the SDR signifies the fraction of eroded material transported to water bodies [47].

We utilized hydrosedimentological station number 61,661,010 operated by the Instituto Mineiro de Gestão das Águas (IGAM) (the station available for the period) to calculate the sediment production observed in the field. We computed the fluxes for 2017, 2019, and 2022 based on monthly data from the monitoring bulletins of the Furnas UHE reservoir provided by the Agência Nacional de Águas e Saneamento Básico (ANA) [48]. Subsequently, we developed the curve relating to the total transported sediments and the water flow for the set of fluxes for 2017, 2019, and 2022 and compared the sediments observed with those estimated with InVEST.

2.4. *SOM and SOC Models*

Unlike the soil losses obtained with InVEST, the SOC and SOM contents were spa- tialized and calculated in ArcGIS for each coffee sample. Here, 46 soil samples were collected from coffee cultivation, 1 for each coffee plot, every January in 2017, 2019, and 2022. These samples weighed approximately 600 g and were collected at a depth of 0 to 20 cm (Figure 3A–

C). The SOM was determined by Cooxupé laboratories using the dry quantification methodology in a muffle furnace via incineration [30]. The SOC content was calculated by multiplying the SOM content by the van Bemmelen constant of 0.58 [49,50]. After, we calculated the average SOC and SOM contents in two intervals: from 2017 to 2019 and from 2020 to 2022. This approach aimed to reduce the impact of variations in the results due to sampling and analysis issues.

For each collected sample, a location point was recorded. Each point was then assigned a row in the ArcGIS attribute table with the information "SOM content" for each year. We spatialized this SOM in a raster format via ordinary kriging interpolation using the Geostatistical Wizard in ArcGIS 10.8 for all areas because coffee plantations (including coffee plants and bare soil) occupy approximately 80% of the area, distributed throughout the entire region, thus facilitating interpolation. The SOC losses were derived by multiplying the SOM values by the soil losses [51] in raster format.

3. Results

3.1. RUSLE Factors and Soil Losses

The R, K, and LS factors of the RUSLE are depicted in Figure 4A, 4B and 4C, respec- tively. The C factor in 2017, 2019, and 2022 is illustrated in Figure 4D, 4E and 4F, and the P factor in Figure 4G, 4H and 4I, respectively.

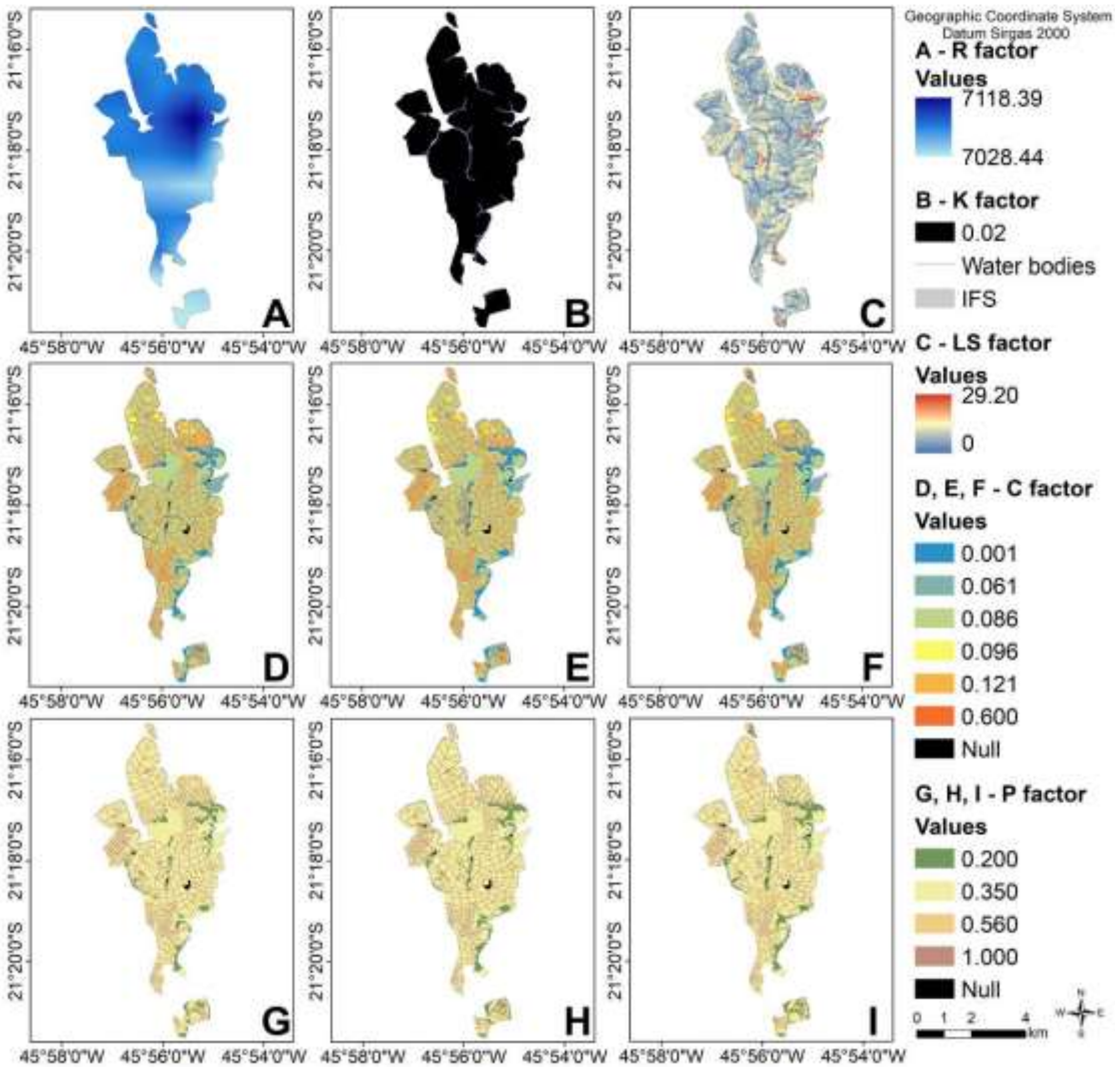


Figure 4. RUSLE factor maps: (**A**) erosivity factor R; (**B**) erodibility factor K; (**C**) topographic factor LS; (**D**) C factor in 2017; (**E**) C factor in 2019; (**F**) C factor in 2022; (**G**) P factor in 2017; (**H**) P factor in 2019; (**I**) P factor in 2022.

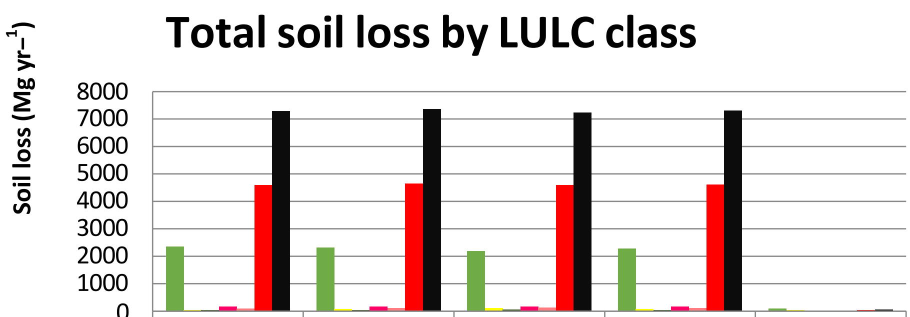
The R values ranged from 7028.44 to 7118.39 MJ mm ha^{-1} h^{-1} yr^{-1}. These values were considered medium–high according to a national erosivity study [52] and high according to a global erosivity study [53]. The highest R values were found in tropical areas [54] due to rainfall rates. Rainfall erosivity significantly affects the soil loss in agricultural lands in these locations.

The K value for Latosols was 0.02 Mg h MJ^{-1} mm^{-1}, classified as moderate [55].

Latosols are naturally deep, more resistant to water erosion, well drained, and clay- textured [56].

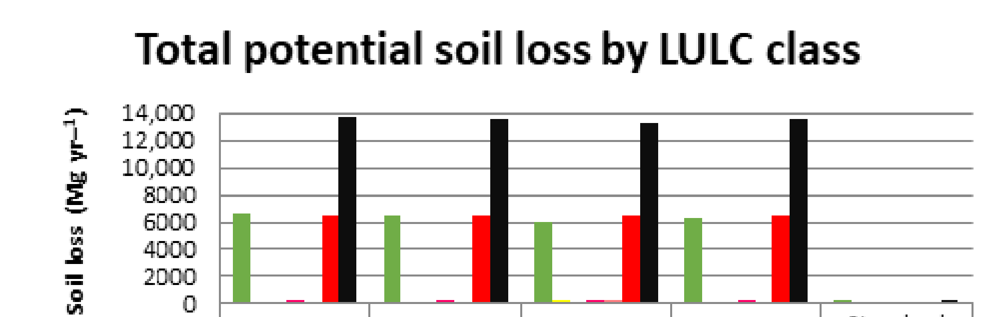
The LS values ranged from 0 to 29.20, with 57.25% of the area below an average of 5.40 on the less steep slopes. An increase in the LS enhances the speed of runoff and soil loss rates [57].

The values of C and P in the coffee plantation were low, indicating good canopy coverage and efficient agricultural management practices. We observed the lowest C and P values in native forests, while the highest were found in bare soil at the coffee rows and access roads, where vegetation cover is less protective against soil degradation. Additionally, given the high R values, maintaining low C and P values is essential for mitigating soil losses [24]. The total, potential, and average soil losses, categorized by LULC class, are presented in Figures 5–7.



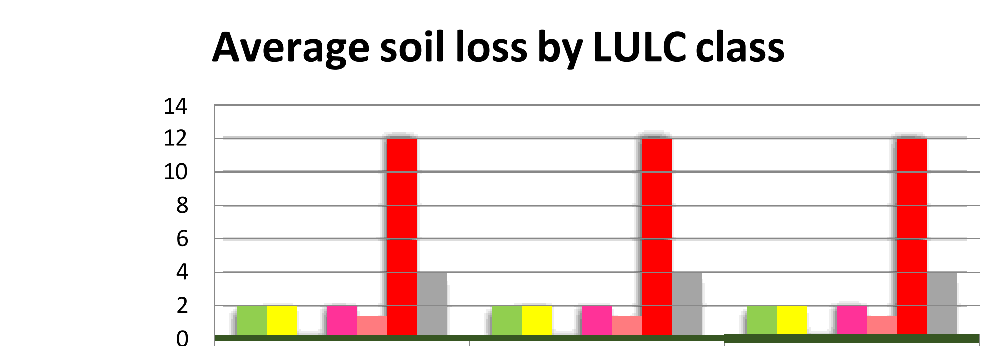
	2017	2019	2022	Average	Standard deviation
Coffee	2347	2319	2185	2284	87
Eucalyptus	47	83	112	81	33
Native forest	42	39	55	45	9
Other crops	171	169	174	171	3
Pasture	96	113	123	111	14
Bare soil	4588	4645	4589	4607	33
Sum	7291	7368	7238	7299	65

Figure 5. Total soil loss categorized by LULC class in 2017, 2019, and 2022.



	2017	2019	2022	Average	Standard deviation
Coffee	6657	6421	5970	6349	349
Eucalyptus	102	143	270	172	88
Native forest	61	56	64	60	4
Other crops	262	253	278	264	13
Pasture	160	200	223	194	32
Bare soil	6423	6504	6424	6450	46
Sum	13,665	13,577	13,229	13,490	231

Figure 6. Total potential soil loss categorized by LULC class in 2017, 2019, and 2022.



	2017	2019	2022
Coffee	1.77	1.8	1.77
Eucalyptus	1.92	2.06	1.8
Native forest	0.31	0.26	0.32
Other crops	2.01	1.97	2.08
Pasture	1.07	1.22	1.12
Bare soil	12.23	12.3	12.22
Average	3.58	3.61	3.55

Figure 7. Average soil loss categorized by LULC class in 2017, 2019, and 2022.

The difference between total soil loss and potential soil loss is presented in Table 3.

Table 3. Differences between total soil loss and potential soil loss.

2017 Year	Total Soil Loss (Mg yr^{-1})	Total Potential Soil Loss (Mg yr^{-1})	Difference (Mg yr^{-1})	Difference (%)
Coffee	2346	6657	4310	283
Eucalyptus	47	102	55	217
Native forest	42	61	19	145
Other crops	170	261	90	153
Pasture	95	160	64	167
Bare soil	4588	6423	1834	139
Sum	7290	13,665	6374	187

The average soil loss is presented in Figure 7.

We observed the highest average soil losses in bare soil and the lowest in native forests, consistent with the pattern of total soil loss. Total soil losses ranged from 7236.97 to 7368.03 Mg yr^{-1}, while total potential soil loss ranged from 13,227.84 to 13,665.37 Mg yr^{-1}. Potential soil losses in coffee plantations without conservation practices increased from 2346.91 to 6657.15 Mg yr^{-1}. This indicates that, with the maximum C and P factors in this LULC category, soil losses would be significantly higher. This finding highlights the effectiveness of conservation management practices in reducing P values and the presence of Brachiaria in coffee rows to reduce the C factor, mitigating water erosion.

Regarding water erosion and eroded material, Figure 8 illustrates the sediment curve relative to water discharge.

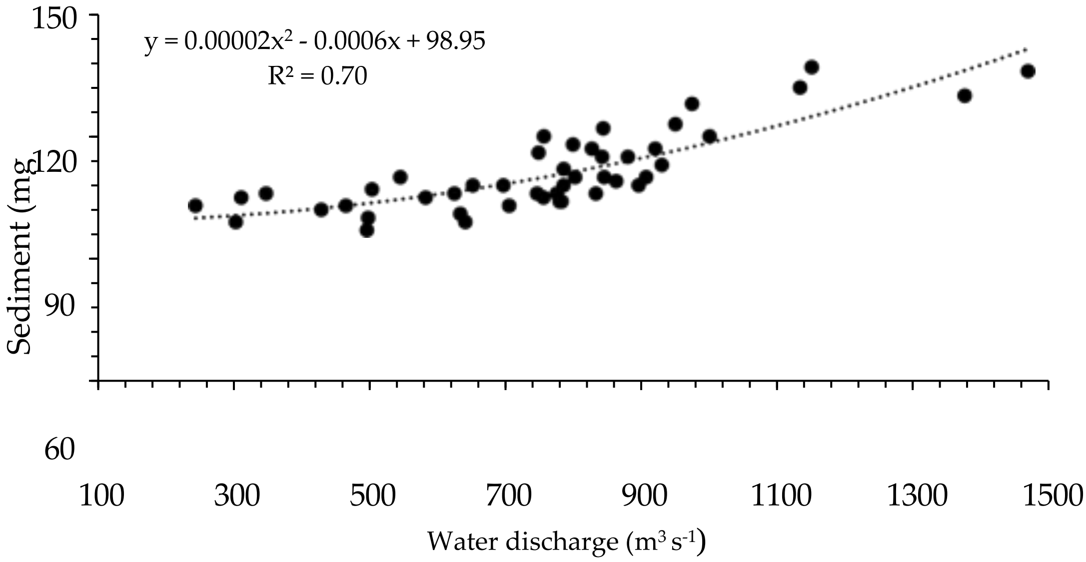


Figure 8. Water discharge–sediment transport curve.

Table 4 shows the SDR estimated with the InVEST software and the observed values.

Table 4. Estimated and observed SDR values for the years 2017, 2019, and 2022.

Year	Estimated SDR (Mg ha^{-1})	Observed SDR (Mg ha^{-1})	Variation (%)
2017	0.28	0.29	4
2019	0.30	0.34	12
2022	0.25	0.28	11

The variation ranged from 4% to 12%. A variation below 20% is considered acceptable, indicating the results' accuracy [58]. The spatial distribution of the soil losses is illustrated in Figure 9.

3.2. Soil Organic Matter (SOM) and Carbon (SOC) Losses

The weighted average SOM content ranged from 2.0 to 4.7% between 2017 and 2022 (Figure 10). The data for SOC losses are presented in Table 5.

The SOM content is within the range typically observed in Cerrado soils, approxi- mately 5%, which is considered high [59]. In tropical regions, SOM levels are generally lower, typically ranging from 1% to 3%, due to climatic conditions such as high tempera- tures and humidity that accelerate organic matter decomposition and carbon mineralization. However, when considering all soil types globally, the average SOM content generally ranges between 2% and 4% [60].

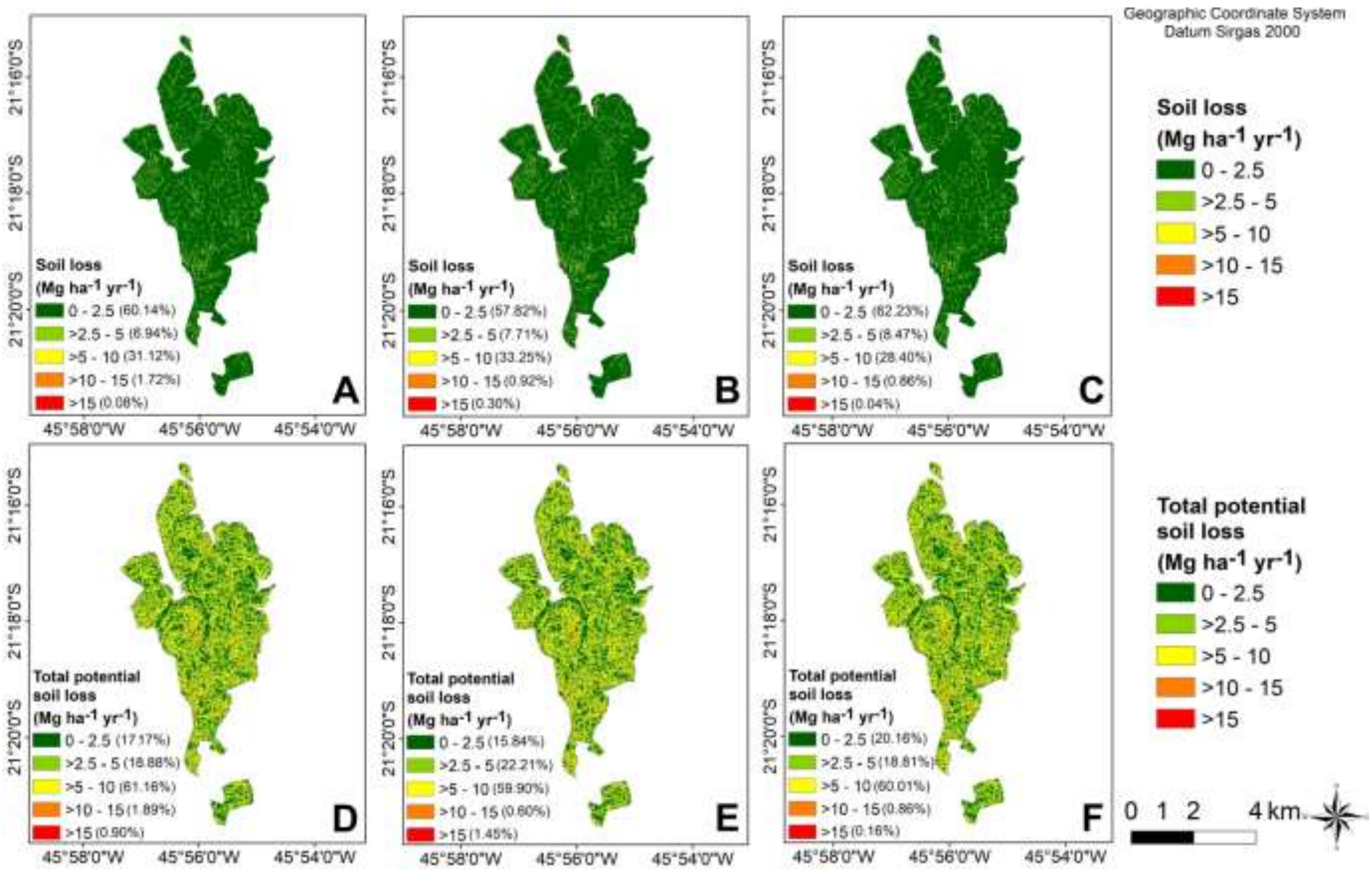


Figure 9. Spatial distribution of soil losses: (**A**) 2017, (**B**) 2019, (**C**) 2022. Total potential soil losses: (**D**) 2017, (**E**) 2019, (**F**) 2022.

Table 5. Differences in SOC losses in two periods.

SOC Loss	Period 1 * Area (ha)	% of the Area	Area (ha)	Period 2 ** % of the Area	Difference (%) Period 2–Period 1
0–5	729.77	35.67	780.30	38.14	2.47
>5–10	229.34	11.21	247.96	12.12	0.91
>10–15	260.44	12.73	274.96	13.44	0.71
>15–25	96.97	4.74	158.14	7.73	2.99
>25–50	343.50	16.79	283.97	13.88	−2.91
>50–100	83.88	4.10	135.23	6.61	2.51
>100–200	199.67	9.76	112.52	5.50	−4.26
>200	102.29	5.00	52.78	2.58	−2.42
	2045.90	100	2045.9	100	100

* Period 1 = 2017–2019; ** Period 2 = 2020–2022.

The SOM variation might be attributed to (i) the different management practices for each coffee plot, such as weeding, pruning, fertilization [61], spacing, and the presence of brachiaria grass between coffee rows [62]; (ii) the heavy mechanization starting in 2019, especially with sweeping in the coffee plantation; (iii) the proximity to the reservoir, as higher soil moisture levels tend to accelerate organic matter decomposition [63]; and (iv) the decrease in rainfall volume recorded between 2015 and 2020 [64].

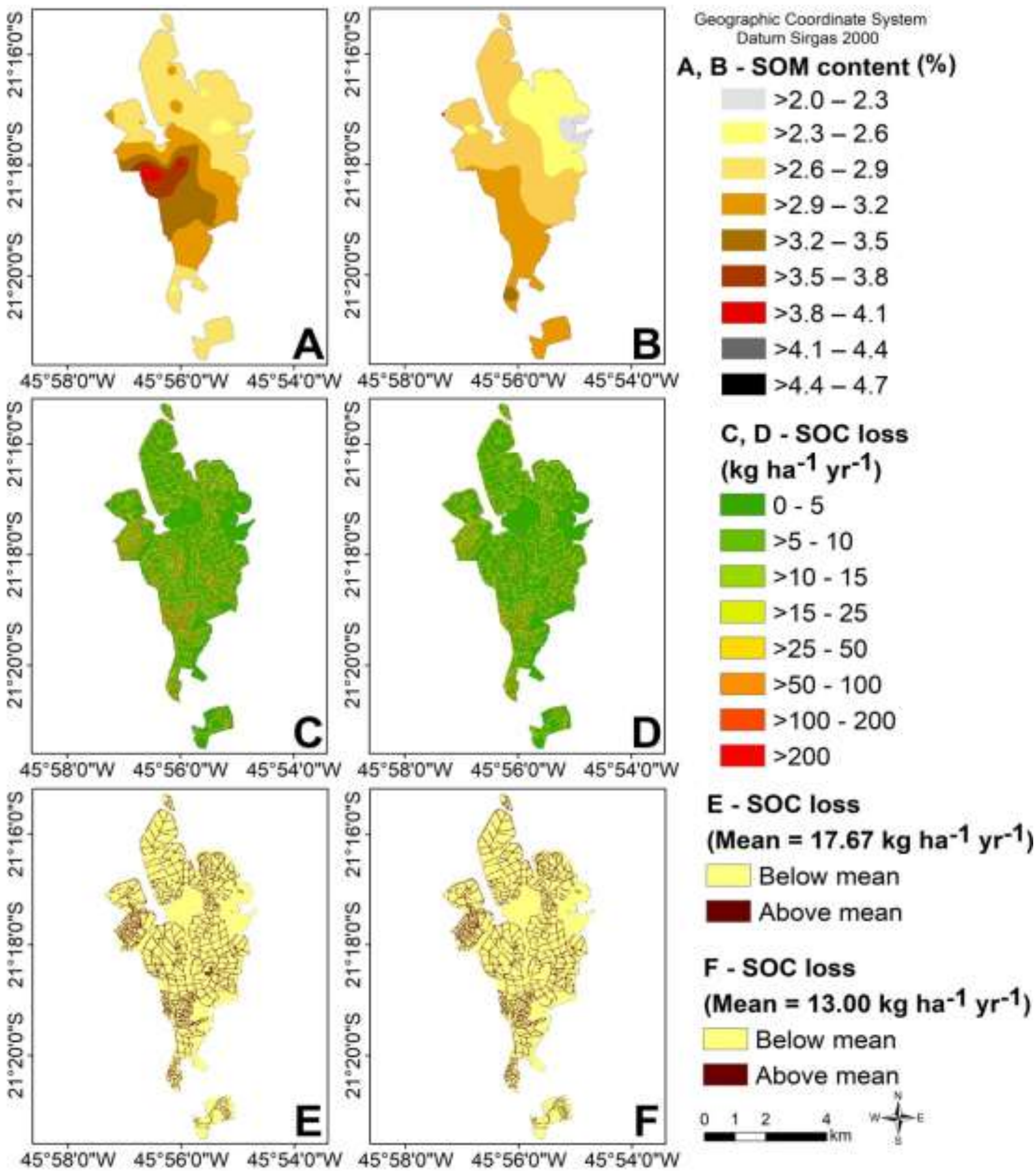


Figure 10. Spatial distribution of SOM levels: (**A**) period 1, (**B**) period 2. Spatial distribution of SOC losses: (**C**) period 1, (**D**) period 2. Values above and below average SOC losses: (**E**) period 1, (**F**) period 2. Period 1 = 2017–2019; period 2 = 2020–2022.

4. Discussion

4.1. Soil Losses

Figure 9 illustrates the difference between estimated soil loss and soil loss in the absence of conservation practices. The average soil losses in coffee cultivation areas ranged from 1.77 to 1.80 Mg ha^{-1} yr^{-1}, which is consistent with findings from nearby sub-basins reporting a maximum soil loss of 2.91 Mg ha^{-1} yr^{-1} [65–68]. These rates were considerably lower than those observed in another study [69], which reported values of 31.11, 32.83, and 23.9 Mg ha^{-1} yr^{-1} in regions with Latosol of recent agricultural expansion in the Brazilian Cerrado. This difference can be attributed to the following: (i) the difficulty of implementing conservation practices due to the large area size; (ii) the use of conventional tillage; (iii) high LS factor; (iv) agricultural expansion associated with deforestation and bared soil; and (v) the high erodibility, which reached a value of 0.72 Mg h MJ^{-1} mm^{-1}, and cover management practices, which reached a value of 0.96.

The less steep terrain, combined with the conservation agricultural practices in coffee cultivation at Conquista, provided soil protection against precipitation, particularly due to (i) the maintenance of vegetative residues between coffee rows for part of the year, which attenuated surface runoff velocity and increased the concentration of soil organic matter (SOM) at the soil surface; (ii) planting along contour lines, facilitating agricultural management and reducing the dispersion of vegetative residues; (iii) fertilization aimed at promoting a denser and healthier vegetative cover; (iv) vegetative strips on slopes and along the edges of rural roads; (v) controlled machinery traffic, particularly during the harvest season; (vi) irrigation management to prevent excess water in the soil; and (vii) continuous monitoring of productivity [70].

The average soil losses in coffee cultivation remained virtually constant from 2017 to 2022. However, despite the low soil loss rates, they need to be reduced to levels comparable to those observed in native forests, ranging from 0.26 to 0.32 Mg ha^{-1} yr^{-1}, in order to ensure the long-term sustainability of agricultural systems [1]. Although these losses are currently stable, they are not yet associated with a reduction in productivity, which is a positive sign. In tropical areas, due to the high rainfall, soil erodibility, and rapid changes in land use and land cover, reducing soil losses should be progressively prioritized. As evidenced in Figure 8, the agricultural practices adopted, combined with the maintenance of native vegetation, are essential in this regard, not only to mitigate soil losses but also to maintain and increase SOC stocks. The importance of vegetation cover in mitigating soil losses, particularly of carbon (C) and P, which are directly influenced by human activities and exhibit more rapid changes, is illustrated by the disparity between the soil and potential soil losses (Figures 5 and 6).

Studies on erosion and phosphorus have concluded that more than 50% of the global loss of this element in agriculture can be attributed to soil degradation, particularly water erosion [6]. Water erosion releases phosphorus bound to soil minerals in agricultural lands into water bodies, adversely affecting aquatic ecosystems. Thus, studies on phosphorus content in water can be combined with research on water erosion and soil loss. Another issue, especially in Latin America, is the inefficient management of organic phosphorus, which is linked to geological reserves. Therefore, reducing soil erosion is essential for maintaining phosphorus stocks [6].

The minimal variations in average soil losses and the absence of reduction in crop productivity over time may demonstrate the relevance of agricultural practices in the context of the biennial nature of coffee. Moreover, the lower the losses of SOC, the lower the cost associated with replenishing SOM through fertilization. However, it is necessary to diversify management approaches with alternating strategies from year to year, increasingly aiming at reducing such rates and enhancing carbon sequestration.

We observed the highest average rates of soil loss in bare soil areas, corresponding to access roads between coffee rows and rural roads. The values ranged from 12.23 to 12.30 Mg ha^{-1} yr^{-1}. These values were lower than those reported in the Rio Grande Basin [71] and in steep areas in Colombia, both exceeding 100 Mg ha^{-1} yr^{-1} [72]. This difference may be attributed to (i) the bare soil being predominantly located in coffee rows, reducing sediment transport via runoff; (ii) the increased SOM due to fertilization and maintenance of vegetative residues that fall onto the soil during part of the year until harvesting; and (iii) the lower C value.

The average soil losses in eucalyptus ranged from 1.80 to 2.06 Mg ha^{-1} yr^{-1}, surpass-ing the values reported in Rio Grande do Sul (0.12 to 0.81 Mg ha^{-1} yr^{-1}) [41] and in Bahia (1.46 Mg ha^{-1} yr^{-1}) [73]; nevertheless, they were lower than the results in deforested areas in the Brazilian Cerrado (33 to 38 Mg ha^{-1} yr^{-1}) [69]. Depending on the management practices employed, eucalyptus cultivation can intensify soil losses due to (i) the shading created by the vegetative canopy, hindering the growth of other species and diminishing soil aggregation and structure [74], and (ii) its shorter cultivation cycle of 6 years compared with that for coffee, resulting in reduced vegetation cover for prolonged periods.

We observed the lowest average soil losses in native forests, ranging from 0.26 to 0.32 Mg ha^{-1} yr^{-1}, lower than the values for forests in Paraná state (1.78 to 6.68 Mg ha^{-1} yr^{-1}) [75]. These rates were similar for nearby sub-basins (0.06 Mg ha^{-1} yr^{-1}) [67]. Preserving vegetative cover is essential for reducing soil erosion, as it enhances water infiltration, reduces runoff, and mitigates sediment release and transport [68]. Furthermore, restoring native vegetation contributes to soil loss reduction [67]. Vegetation provides additional benefits by increasing soil moisture and SOM levels and delivering ecosystem services, such as promoting the presence of pollinating insects, thereby optimizing overall production [74].

For pasture and other crop classes, the average soil losses ranged from 1.07 to 2.08 Mg ha^{-1} yr^{-1}, classified as very low [48] due to the predominance of flat to gently undulating terrain. Pastures offer more efficient soil protection than eucalyptus.

4.2. Soil Organic Carbon (SOC) Losses

Although there was minimal variation in the average soil loss, the average SOC losses decreased from 17.67 to 13.00 kg ha^{-1} yr^{-1}. Most areas recorded values below the average during this period. This variation can be attributed to the decrease in total soil losses from 2019 to 2022 (Figures 5 and 6). These average SOC losses were lower than the values estimated for Ethiopian agricultural lands (14.4–32.8 kg ha^{-1} yr^{-1}) [22] and in experimental farm studies in the USA (117–358 kg ha^{-1} yr^{-1}) [74]. Lower SOC losses indicate (i) reduced interference in the global SOC cycle; (ii) lower costs associated with fertilizer replenishment; and (iii) higher agricultural soil quality [75].

Controlling water erosion can improve soil carbon sequestration [76], especially on steep terrain. Thus, despite low rates of SOC loss, the long-term implications include restricting carbon sequestration and damaging soil quality [77]. The SOC losses observed in our study were lower in a comparative analysis of the SOC losses due to water erosion under varied conditions (i.e., climate, slope, soil, and management) with a wide range of SOC loss values from 1000 to 3000 kg ha^{-1} yr^{-1} for uncultivated soils in very humid regions to less than 15 kg ha^{-1} yr^{-1} for forests and other dense vegetation cover types [78]. According to Table 5, areas with SOC losses below 50 kg ha^{-1} yr^{-1} are predominant. These losses can be considered low [77], but there is still potential for improvement. Losses exceeding these values are concentrated in coffee planting rows and rural roads, propor- tional to soil losses. These areas require the most intervention, not only to reduce SOC deficits but also to preserve stock levels through measures such as maintaining native vege- tation, reducing the intensity of coffee sweeping practices, promoting crop diversification, and incorporating Brachiaria species.

SOC losses were associated with soil losses, as shown in Figures 5–7. The total soil loss was greater in 2019, which resulted in a higher average SOC loss as well. In 2022, both losses were lower. Therefore, reducing soil loss can contribute to reducing SOC loss; however, further studies are necessary to corroborate this finding. Various sustainable management practices are employed at Conquista, such as adopting contour farming, applying green manure, and maintaining vegetative cover between coffee rows. These practices improve the soil structure, increase its water retention capacity, and reduce dependence on chemical fertilizers and pesticides, increasing SOC stocks [77]. The average soil and SOC losses also decreased during the study period by the expansion of native forest areas, next to 14%, as evidenced in Table 1. Restoring vegetation, particularly when involving diverse plant species and sustainable management practices, can increase SOC and nitrogen (N) stocks [79]. Despite the lack of data on SOC in native forests, a reduction in soil losses leads to increased SOC fixation, which reduces transport and minimizes deposition in water bodies [76]. Studies on coffee cultivation demonstrate a reduction in soil loss ranging from 7% to 35% with the adoption of effective strategies for mitigating soil erosion, such as increasing vegetation cover and implementing soil conservation practices [80].

The analysis of the impact of agricultural management on SOC levels in tropical climates represents a challenge [18] and requires comprehensive assessment. Practices such as fertilization, composting, no-till, and contour farming—along with agroecological man- agement, which promotes plant diversity—can increase SOC rates in tropical cultivation areas [81] due to enhanced microbial activity. This, perhaps, could be the next goal for future studies in the area.

In the context of coffee production, understanding how the environment reacts to anthropic actions on soils is fundamental for assessing ecosystem services. Thus, integrating agricultural systems with management techniques that control water erosion rates; optimize the application of nitrogen fertilizers; improve soil biological, physical, and chemical attributes; increase water retention; and enhance SOM, SOC, and N stocks are fundamental to minimizing climate change impacts [82].

Even with the limitations related to the calibration of factors for specific regional appli- cabilities [83], the models' inability to capture highly complex landscape interactions [84], the low availability of reliable long-term data, and the lack of information to corroborate in situ validation [85], the RUSLE has proven useful for spatializing water erosion and estimating soil and SOC losses [81]. However, the RUSLE's simplicity allows its application in areas where data for more complex models are scarce, and it is widely used, contributing to the formation of an increasingly robust database and improving the accuracy for different regions [86].

Soil loss studies are highly relevant not only for coffee cultivation but also for other crops. The findings from these studies can contribute, for example, to improving sustain- ability, productivity, and environmental health; these include the following: (i) Erosion control. Since coffee is typically grown in steep or sloped areas, it is more susceptible to erosion. Therefore, maintaining cover crops along planting rows can mitigate soil loss and be applied to other crops, such as grains, fruits, and vegetables. (ii) Reducing the use of fertilizers, as the maintenance of soil organic matter decreases the need for manual soil amendments. (iii) The necessity of using monitoring techniques to assess the spatial distribution of erosion, quantify soil loss, and evaluate soil quality attributes. (iv) Providing a database that offers a better understanding of how climate change affects erosion and the subsequent degradation of soil, particularly in tropical countries.

It is essential to adapt agricultural systems to these warming conditions and extreme weather events [21]. Improved agronomic practices result in SOC increases that can exceed 0.4% per year [87]. This will only be possible with more access to information for farmers, aiming to adopt sustainable practices [88] that prioritize reducing disturbances to the soil, stabilizing and maintaining SOC stocks [89], and combining production and sustainability for a growing population. Brazil is highly dependent on agricultural soils. Given this, the pressure on the agricultural production system will increase [89]. In this context, the study of the Conquista Farm is a good example of the relevance of vegetative cover and conservationist practices in reducing water erosion while maintaining agricultural production and tackling climate change.

5. Conclusions

This study assessed and analyzed the spatiotemporal dynamics of soil and SOC losses due to water erosion in tropical coffee-growing areas in Brazil. Vegetative cover has been crucial in minimizing soil losses, with native forest areas exhibiting the lowest rates and bare soils exhibiting the highest. Therefore, the preservation of native vegetation and the maintenance of vegetation cover along coffee rows, as in sustainable agricultural management practices, have the potential to reduce soil and SOC loss rates in tropical coffee cultivation over a five-year period. However, long-term continued reductions in these rates are necessary.

It is valid to state that modeling soil carbon dynamics faces limitations, particularly in regions with diverse soil types, land uses, climatic conditions, and agricultural management practices. Despite these challenges, studies in this field are crucial for providing a broader understanding of soil carbon trends with speed and efficiency. However, to enhance the reliability of such models, the integration of high-resolution remote sensing data, the development of a robust region-specific database, and the application of machine learning techniques are essential. Furthermore, combining modeling efforts with strategic field measurements for validation enables more informed decision-making for climate change mitigation and sustainable land management. This is particularly impactful when such information reaches land managers and policymakers in an effective manner.

The difference between total and potential soil losses was approximately 305%. This difference can be attributed to the role of ground cover and the agricultural management practices adopted—the maintenance of native forest areas and the presence of ground vegetation along planting rows—which mitigate the values of C and P.

Between 2020 and 2022, the rates of SOC loss remained below average and decreased with the expansion of native forest areas despite the biennial nature of coffee production and LULC changes. To address food security challenges, it is essential to enhance agricultural management practices aimed at increasing SOC stocks and mitigating the impacts of climate change. Future LULC scenario studies can promote agricultural and environmental sustainability and assist managers in understanding the impacts on ecosystem services.

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5 PAPER III - Greenhouse gas emission in tropical coffee-production areas

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Abstract

The adverse effects of climate change are among the main environmental challenges of the 21st century. One of the key players in this process is the greenhouse gas (GHG) emissions. Some of these gases such as carbon dioxide (CO_2) and nitrous oxide (N_2O) come from agricultural activities. The intensity of the GHG emissions associated with agricultural activities varies according to the management practices, including coffee crops produced in tropical areas. This study aimed to estimate the GHG emissions in three coffee farms of 1666, 1772 and 2045 ha, located in the south of Minas Gerais state, in Brazil, over two years, based on emission inventories. This inventory was made according to methodologies from the Intergovernmental Panel on Climate Change (IPCC) adjusted for Brazil, considering the consumption of electricity, fossil fuels, burning wood and fertilizers. In general, the total GHG emissions varied from 3566.35 to 11,067.39 t CO_2eq, from 2.14 to 5.41 t CO_2eq ha^{-1}, and from 2.22 to 6.88 kgCO_2eq kgcoffee^{-1}, respectively. The highest emissions came from urea-based nitrogen fertilizers and burning wood. The results indicate that the adopted agricultural management contributed to mitigating the harmful environmental impacts of GHG emissions. It includes the maintenance of plant residues between coffee rows, the use of non-urea-based fertilizers and the adjusted doses of N according to soil analyses. In addition, the results obtained for the GHG emissions are aligned with the values for Brazilian coffee production; however, it could be reduced by adopting agroforestry systems, increasing the amount of coffee straw in the soil and replacing urea with urea-free fertilizers. Therefore, further studies are still needed to access the impact of agricultural management practices, such as the application of slow-release fertilizers, with or without urease inhibitors.

Keywords: climate change; carbon stock; nitrogen fertilizers; agricultural management; LULC.

1. Introduction

The Industrial Revolution, the population growth, and the rise of industrialization, increased the demand for fossil fuels. At the same time, rapid alterations in land use and land cover (LULC) and the expansion of crop production have amplified climate change (Arfasa *et al.*, 2024). One of the consequences was the escalation of atmospheric CO_2 concentration by 47% (Humayun and Anwar, 2021), resulting in adverse environmental repercussions (Kabir *et al.*, 2023).

The primary driver of climate change is the intensification of the greenhouse gas (GHG) emissions (Bhatti *et al.*, 2024), encompassing carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and water vapor (Florides and Christodoulides, 2009). Among the most impacting GHG emissions, those originating from arable land contribute from 10% to 12% of the annual total values (Linquist *et al.*, 2012). The atmospheric concentration of N_2O raised from 290 ppb in 1940 to 330 ppb in 2017. In this scenario, 60% of the yearly N_2O emissions are attributed to agricultural activities (Hassan *et al.*, 2022; Li *et al.*, 2022). Notably, Brazil ranks prominently among the GHG emitting nations due to deforestation and the conversion of forests into pasture (SEEG, 2021). Conversely, the Brazilian agricultural sector constitutes 24.8% of the gross domestic product (GDP) (CEPEA and CNA, 2023), due to the extensive arable land, favourable soil and climatic conditions, abundant water resources, technological advancements, and intensive fertilizer utilization (Strassburg *et al.*, 2014).

The agricultural sector, which covers 40% of the Earth's surface (Foley *et al.*, 2005), is being increasingly affected by the effects of climate change (Parker *et al.*, 2019; Ahmed *et al.*, 2022). These effects lead to heightened occurrences of extreme weather events, causing crop relocation, yield reduction, and global food and nutritional insecurity (Godde *et al.*, 2021). Coffee cultivation, for example, is highly vulnerable to the impacts of climate change (Pham *et al.*, 2019). The environmental stress caused by climate change modifies flowering and fruiting stages, decreases bean quality, increases the occurrence of pests, and leads to reduced yields (Torres Castillo *et al.*, 2020). The impact of climate change also causes loss of diversity. Approximately 60% of wild coffee species are at risk of extinction (Davis *et al.*, 2019).

Led by Minas Gerais state, Brazil is the main producer and exporter of coffee (*Coffea arabica*), holding more than one-third of the world’s production (ICO, 2008; Tieghi *et al.*, 2024). Solely, the state produced 22 and 29 million bags (each bag 60 kg) in 2022 and 2023, respectively (CONAB, 2024), accounting for nearly 50% of the nation's coffee production. However, this production contributes to greenhouse gas emissions, depending on the management practices adopted (Oliveira Junior *et al.*, 2015).

The main GHG emitted by coffee cultivation are N_2O, CO_2 and CH_4 (Chataut *et al.*, 2023), which originate from the use of electricity, fossil fuels, wood burning and, above all, the application of nitrogen (N) fertilizers and limestone (San Martin Ruiz *et al.*, 2021). The coffee plant is nutritionally demanding, mainly in terms of N, which makes up the cellular structure of plants (Bote *et al.*, 2018). Despite its importance, the large-scale use of N fertilizers causes environmental impacts that harm ecosystems, human health and agriculture itself, through the eutrophication of water bodies, destruction of the ozone layer, intensification of global warming and increased frequency of extreme weather events (Gatti *et al.*, 2021). In this scenario, Brazil is one of the world's largest consumers of N (IFA, 2017). There are published studies on GHG emissions from sugarcane cultivation in municipalities from São Paulo state (Carmo *et al.*, 2013), sugar production in the Brazilian southeastern (De Figueiredo *et al.*, 2010), ethanol production in Minas Gerais state (Claros Garcia and Von Sperling, 2010; Claros Garcia and Von Sperling, 2017) and rice production in Rio Grande do Sul state (Grohs *et al.*, 2020). However, there is a lack of studies regarding such emissions related to coffee production.

Therefore, to promote the reduction of GHG emissions in coffee agribusiness, the present study aimed to establish an inventory of GHG emissions targeting at coffee-producing areas in Minas Gerais State in 2021 and 2022, with the main objective to identify and quantify it sources. For that, we used the GHG protocol from the Intergovernmental Panel on Climate Change (IPCC) adjusted to Brazil, considering the consumption of electricity, fossil fuels, burning wood and fertilizers (WRI and WBCSD, 2011; WRI and UNICAMP, 2015).

2. Materials and methods

2.1. Study area and description

The study was conducted in three large Brazilian coffee production units called Conquista (Alfenas municipality) (Fig. 1A), Capoeirinha (Alfenas and Machado municipalities) (Fig. 1B), and Rio Verde, which comprises two farms: Rio Verde (Conceição do Rio Verde) and Pinheirinho (Cambuquira) (Fig. 1C). All farms belong to the Ipanema Coffees company (Ipanema Agrícola S.A.).

Alfenas and Machado municipalities are part of the Guaxupé Complex, characterized by a terrain of rounded and gentle hills and mountains supported by granulites, gneisses and quartzites (Hasui, 2010). Those are lower-altitude and flat areas consisting of granulites and gneisses, predominantly featuring clayey colluvial and eluvial soils (Silva *et al.*, 2020). The native vegetation is characterized by a transition between the Atlantic Forest and Cerrado biomes (Silva *et al.*, 2021). Cambuquira and Conceição do Rio Verde municipalities are situated in the Serra da Mantiqueira (Brazil, 1983). The area features irregular relief elevations, hills with gentle slopes, and shallow valleys with river plains and expansive alluvial terraces. The predominant vegetation is the Atlantic Forest biome (MapBiomas Project, 2023).

The climate of the area is classified as humid subtropical (Cwb), characterized by dry winters and hot summers with mild rainfall. The rainy season extends from October to March.

In Alfenas and Machado, the average temperature is 21.2 °C, with average precipitation ranging between 1500 and 1750 mm. In Conceição do Rio Verde and Cambuquira, the average temperatures are 20.1 °C and 19.9 °C, with precipitation from 1660 to 1900 mm and 1690 to 1920 mm, respectively (Alvares *et al.*, 2013).

The land use and land cover (LULC) maps are shown in Fig. 2A, 2B, and 2C.

At Conquista, the predominating soils are Ferralsol soil type (World Reference Base for Soil Resources – WRB) (IUSS, 2015) or Red Latosol (Santos *et al.*, 2018), with gently undulating terrain and altitudes ranging from 760 to 890 m (Fig. 3A and 4A). At Capoeirinha, the predominating soils are Ferralsol or Red Latosol, and Red-yellow Latosol, with undulating terrain and altitudes ranging from 781 to 971 m (Fig. 3B and 4B). At Rio Verde unit, Acrisol (WRB) (IUSS, 2015) or Red Argisol and Ferralsol or Red-yellow Latosol (Santos *et al.*, 2018) predominate, with gently undulating terrain and altitudes ranging from 839 to 1345 m (Fig. 3C, 3D, 4C, and 4D).

Harvesting is 100% mechanized in Conquista, 98% in Capoeirinha, and 69% in Rio Verde. Manual harvesting occurs in approximately 12% of the total coffee area, mainly in the higher altitudes of Rio Verde. At Conquista, spacing varies from 3.5 to 4.0 m between planting rows and 0.5 to 1.0 m between plants; at Capoeirinha, it ranges from 2 to 4.8 m and 0.5 to 1.5 m; and at Rio Verde unit, it ranges from 2 to 4 m and from 0.5 to 2 m, respectively.

In all farms, the productive area is managed with agronomic practices including fertilization, weed, pest and disease control, pruning management and post-harvest treatments. Soil and foliar analyses are conducted to determine the quantity and intensity of fertilization during the coffee farming year, from September to April. Typically, three fixed fertilizations and an optional fourth are carried out according to technical recommendations and the agronomic needs of the crops. In addition to these analyses, factors as irrigation type, dryland or irrigated planting, and expected production are considered. The coffee varieties include Acaiá, Bourbon, Mundo Novo, Arara, Topázio, Catuaí, Icatú, Paraíso 2, Catucaí, Rubi, Acauã, and Geisha. In 2021 and 2022, the total coffee production in 60 kg bags was 122,934 and 52,082, respectively, with 68,197 and 20,631 accounting for Conquista, 30,857 and 17,458 for Capoeirinha, and 23,880 and 15,138 for Rio Verde.

2.2. Calculations

GHG emissions were calculated following the methodologies from IPCC (IPCC, 2006; IPCC, 2019), from the technical notes of the Getúlio Vargas Foundation - FGV (FGV, 2011; FGV, 2023), and from the World Resources Institute - WRI (WRI and UNICAMP, 2015). For these, in 2021 and 2022, data on electricity consumption in megawatt-hours (MWh), consumption of fossil fuels (L), wood (t), liquefied petroleum gas (LPG) (t), urea and non-urea N fertilizers (t), limestone (t) and gypsum (t) were gathered for each unit (Table 1).

We calculated the CO_2eq emissions from electricity consumption according to Equation 1. The emission factor (EF) was 0.1264 for 2021 and 0.0426 for 2022, in tCO_2 MWh^{-1} (Brazil, 2023a).

The fossil fuel emissions were categorized into total emissions and biogenic emissions, in t CO_2. Total emissions refer to diesel and gasoline, while biogenic emissions refer to biodiesel and ethanol. Biogenic CO_2 arises from biomass burning and generates emissions considered climate-neutral since it is produced in the biological cycle (WRI and UNICAMP, 2015). For this purpose, we used Equation 2. The emission factors were 2.6 for diesel, 2.46 for biodiesel, 2.2 for gasoline, and 1.58 for ethanol, in $kgCO_2$ L^{-1}.

The average biodiesel content in diesel fuel was 11.5%. We opted for the mean value since biodiesel content in diesel varied periodically over the two years. Meanwhile, the ethanol content in gasoline remained constant at 27% in 2021 and 2022 (Brasil, 2011; Brasil, 2012), aiming to promote the use of biofuels to reduce GHG emissions.

We calculated the emissions from wood burning and vegetable waste using Equation 3. Both have three emission factors according to the emitted gas. The emission factors for CO_2, CH_4, and N_2O from wood burning are 1817.14, 5.43, and 0.07 kg t^{-1}, respectively, and for vegetable waste are 1161.16, 3.48, and 0.05 kg t^{-1}, respectively (WRI and UNICAMP, 2015).

To estimate the emissions of N_2O from N fertilizer consumption, we determined the kg of N for each fertilizer, as shown in Equation 4. The origin of this N was categorized into urea-based and non-urea-based compounds. The emission factor is 0.02235 kgN_2O kgN^{-1} and accounts for both direct and indirect N_2O emissions (FGV, 2023).

We calculated the direct CO_2 emissions from urea-based nitrogenous fertilizers as Equation 5. Unlike other nitrogenous fertilizers, urea-based nitrogenous fertilizers contains C, thus also emitting CO_2. The EF is 0.7333 $kgCO_2$ $kgurea^{-1}$ (FGV, 2023). The CO_2 emission from limestone was determined by Equation 6. The EF is 0.4767 $kgCO_2$ $kglimestone^{-1}$. The emission of CO_2 from LPG was calculated using Equation 7. The EF is 2.93 $kgCO_2$ $kgLPG^{-1}$ (FGV, 2023).

The conversions of N_2O and CH_4 into CO_2 equivalent are listed in Equations 8 and 9. As the Fifth Assessment Report (AR5) (IPCC, 2013), the Global Warming Potential (GWP) of N_2O is 265 and of CH_4 is 28, which signifies the capacity of those gases to retain heat over 100 years compared to CO_2 (GWP-100). This is the most used method for converting gases into CO_2eq.

3. Results

3.1. Electricity consumption

The emission factor (EF) related to the electricity consumption varied according to the Brazilian energy matrix used in both years. Electricity generation from non-renewable sources accounted for 55.3% in 2021 and 52.6% in 2022, which amounts to a reduction of 2.7% (Brazil, 2022; Brazil 2023b). In 2022, there was a reduced use of coal-fired power plants and natural gas plants.

The variation in electricity consumption is due to the biennial coffee harvesting, and primarily occurs during coffee processing. Due to the higher coffee production and processing in 2021, electricity consumption was greater. However, the GHG emission represents less than 5% of the total emissions, which can be considered low due to the predominance of renewable sources in electricity production in Brazil (Brazil, 2022; Brazil, 2023b). For comparison, in European Union, the average EF from electricity were 0.280 and 0.270 tCO_2 MWh^{-1} in 2021 and 2020 (Bastos *et al.*, 2024), respectively. In Brazil, in the same years, the average EF were 0.126 and 0.042 tCO_2 MWh^{-1} in 2021 and 2022, respectively. In Colombia, one of the world's major coffee producers, the EF in 2020 was 0.182 tCO_2 MWh^{-1} (Climate Transparency, 2020).

The GHG emissions generated by electricity consumption in each farm employed in the present study in 2021 and 2022 are illustrated in Fig. 5.

3.2. Consumption of fossil fuels and wood burning for mobile and stationary sources

Regarding stationary sources, wood burning in coffee drying is the primary source of GHG emissions. The wood used in the production units is dry eucalyptus chips, with an average density of 175 kg m^{-3}. In Conquista, there is also vegetable waste, such as coffee straw, which generates lower emissions than wood chips.

The higher emissions from wood burning result in emissions considered climate-neutral due to photosynthesis (IPCC, 2013). Generally, the standard economic cycle for eucalyptus is 6 years (Zhang and Wang, 2021). Subsequently the emissions caused by burning are compensated due to the previously sequestered CO_2 in the photosynthetic process. Therefore, there is compensation, making the carbon derived from biomass neutral, mitigating direct emissions. However, wood burning generates emissions of CH_4 and N_2O, accounted for as direct emissions and converted into CO_2eq.

The consumption of diesel, biodiesel, gasoline, ethanol, and LPG generates emissions from mobile sources, which varies according to the number of coffee bags. The consumption of fossil fuels is justified by rural technological advancement, especially due to the replacement of manual labour by the agricultural mechanization. At Conquista and Capoeirinha, there is a greater use of agricultural machinery, such as tractors and harvesters, which is favoured by the flat topography. Conversely, the undulating and strongly undulating terrain in Rio Verde requires manual harvesting.

In Conquista, emissions from stationary sources came from wood burning and vegetable waste; in Capoeirinha and Rio Verde, only from wood burning. There was a reduction in total emissions from 2021 to 2022 proportional to the decline in coffee production, except for wood burning in Rio Verde. Table 2 explicit the emissions from stationary and mobile sources at Conquista. Table 3 contains the emissions from stationary and mobile sources at Capoeirinha, and Table 4 contains the emissions from stationary and mobile sources at Rio Verde.

3.3. Nitrogenous fertilizer, gypsum, and limestone consumption

In 2021 and 2022, the major contributors to N emissions at Conquista were urea (45% of N), urea-based compounds (30% of N), and non-urea-based (33% of N) fertilizers. Although urea consumption is lower than other fertilizers, the high N content (45%) combined with C in its composition increases greenhouse gas emissions. In 2021, at Capoeirinha, the highest N_2O emissions came from urea, urea-based, and non-urea-based fertilizers. Conversely, in 2022, highest N_2O emissions in this unit came from urea and urea-based fertilizers. In 2021, at Rio Verde, emissions came mainly from urea-based and non-urea-based compounds; In 2022, emissions in this unit came from urea and urea-based fertilizers. Fig. 6 illustrates the consumption of nitrogenous fertilizers, limestone, and agricultural gypsum per production unit, in 2021 and 2022 and Fig. 7 illustrates the N_2O emissions from fertilizers in 2021 and 2022.

3.4. Nitrogenous fertilizer, gypsum, limestone and total emissions

The CO_2eq emissions from nitrogenous fertilizers, limestone, and agricultural gypsum are depicted in Fig. 8., whose values ranged from 2098.50 to 3679.50 t CO_2eq. in 2021, and 2054.00 to 4309.00 t CO2eq. in 2022. The total CO_2eq emissions from all sources are depicted in Fig. 9, for 2021 and 2022. In 2021, emissions ranged from 3628.74 to 11067.39 t CO_2eq. and in 2022 from 3566.35 to 8416.87 t CO2eq.

4. Discussion

Relatively to 2021, in 2022 it was observed a reduction in total CO_2eq and CO_2eq ha^{-1} emissions and increase in CO_2 emissions by kg of coffee in all studied areas. This variation is associated with the biennial nature of the coffee production and the strong impact of frosts in the region (O Tempo, 2021). Total emissions are higher in Conquista because it (I) has the largest area dedicated to coffee production, (II) uses entirely mechanized harvesting, and (III) consumes more resources due to processing and commercial logistics compared to the other units. The highest emissions came from fertilizers, except in 2021 due to higher wood consumption. The total emissions and average emissions per unit are illustrated in Fig. 10.

The GHG emission, in kgCO_2 per kg of coffee, ranged from 2.22 to 6.88 (Figure 10), aligned with the Brazilian emission rates, which ranged from 1.9 to 4.6 kgCO_2 per kg of coffee (MCTI, 2018), and 4.7 $kgCO_2$ per kg of roasted coffee (WWF, 2022). This difference is attributed to the exceptional emission rate occurred in 2022 at Conquista, as the resources were consumed normally, but production was lower due to frosts. Nonetheless, the rates obtained in the present study were lower than those obtained in Colombia (ranging from 9.8 to 30 kgCO2 per kg), Vietnam (6.5 kgCO2 per kg), and Indonesia (reaching up to 50 kgCO2 per kg of coffee) in recent years (WWF, 2022) due to I) deforestation, especially on Indonesia; II) clearing land for plantations; III) less renewable energy matrices; IV) use of non-renewable firewood or charcoal burning; V) N overdose, especially in Vietnam and VI) inefficient mechanization.

Depending on the management system employed, the CO_2 emission rate per kg of coffee can be lower or higher in comparison to other production areas. For example, the rates obtained by Rikxoort *et al.* (2014) in Central America areas across different planting systems ranged from 6.2 to 10.8 $kgCO_2$ per kg of coffee. The higher values obtained by these authors are explained due to (I) the absence of foliar and soil analyses to determine the amount of fertilizers to be used; (II) the greater quantity of applied nitrogenous fertilizers aiming to compensate for aspects like light incidence, water resources, and coffee age; and (III) to the high emissions due to fermentation and wastewater production. These values obtained in the present study were also lower than the corresponded global average rate for green coffee, which was 7 $kgCO_2$ per kg of coffee (Nemecek *et al.*, 2015). Contrarywise, other studies focusing in Central America, pointed out CO_2 emission rates corresponding to 1.77 $kgCO_2$ per kg of coffee (Killian *et al.*, 2013), 0.51 to 0.64 $kgCO_2$ per kg of coffee (Arellano and Hernández, 2023) and 0.12 to 0.67 $kgCO_2$ per kg of coffee (Noponen *et al.*, 2012). Such differences could be explained due to (I) very low utilization of synthetic nitrogenous fertilizers, especially urea-based ones; (II) smaller cultivated areas preferentially using organic fertilizers; (III) shade-grown and agroforestry planting systems, which fix more N;

(IV) organic cultivation system and (V) manual harvesting.

In our study, the highest GHG emissions in the three areas came from the use of nitrogenous fertilizers, except in 2021 at the Conquista unit, due to consumption of burning wood and fossil fuels associated to the high production (Noponen *et al.*, 2012; Walling and Vaneeckhaute, 2020; Chataut *et al.*, 2023; He *et al.*, 2023). The use of fertilizers is due to climatic seasonality and tropical soils, particularly Latosols, which are naturally acidic with low natural fertility and reduced nutrient availability (Fisher *et al.*, 2020). Tropical regions have higher fertilizer losses due to volatilization and leaching due to high precipitation and temperature (Signor and Cerri, 2013). However, increasing the use of N fertilizers does not proportionally increase crop yields (Guo *et al.*, 2022), as observed in tomato and wheat-rice rotations in China (Zhao *et al.*, 2015; Du *et al.*, 2019), where it was observed a significant increase in N_2O emissions ranging from 10.6% to 243%, while the production increased 5% for tomato and 6.1% for wheat-rice.

The highest coffee quality corresponds to those produced in Rio Verde (G1, 2023) due to altitude, climate, topography (Martins *et al.*, 2020; Tassew *et al.*, 2021) and differentiated agricultural management (Cerri *et al.*, 2007). Factors as the absence of agricultural machinery in steeper areas, manual harvesting, maintenance of vegetative residues in coffee rows and a larger area allocated to native forests fix more carbon and N in the soil and reduce GHG emissions.

It is important to point out that the emissions were calculated using IPCC emission factors adapted for Brazil. Although IPCC guidelines are widely used globally, there are discrepancies regarding emission factors for different regions (Chataut *et al.*, 2023), with a lack of data for tropical (Erickson *et al.*, 2002) and/or developing countries (Walling and Vaneeckhaute, 2020). Higher N_2O emission factors in tropical climates can result in final emission rates 21% higher (Mazzetto *et al.*, 2020).

Another point to consider is the results obtained by indirect methods. Although reliable, such a methodology can ignore factors such as the differentiation between slow-release and normal urea, a fertilizer with or without urease inhibitors and or the fractional application of fertilizers (Wang *et al.*, 2021). According to Smith *et al.* (2012) and Harty *et al.* (2016), the substitution of urea fertilizers by ammonium nitrate and calcium nitrate can increase direct N_2O emissions. However, Morais *et al.* (2011) and Mazzetto *et al.* (2020) suggest that emissions from urea fertilizers are lower. Lyu *et al.* (2021) found that fractionated application of fertilizers over time reduces N_2O emissions and the losses by volatilization, denitrification and leaching (Singh *et al.*, 2005). Furthermore, as Sikora and collaborators (2020) report in their study, the use of controlled-release fertilizers can reduce final N_2O emissions by up to 30%. Therefore, one of the alternatives to improve the calculation methodologies is to develop more accurate emission factors that encompass these variables in experimental fields.

The GHG emissions obtained in the present study are compatible with the reference values for Brazilian coffee production. Some applied techniques already contribute to reducing GHG emissions, such as the intercropping vegetation between coffee rows, the soil and foliar analyses for timely and accurately dosed N application, and the use of fertilizers with urease and nitrification inhibitors (Cerri *et al.*, 2013). Even without considering carbon sequestration, which would reduce GHG emissions significantly (Imaflora, 2021), these values were lower than the global average. However, the introduction of small areas of agroforestry systems that offer shade, the return of coffee straw to increase C stocks in the soil and the preference for ammonia-based fertilizers contribute to reducing N_2O emissions (Signor and Cerri, 2013; Qiao *et al.*, 2015), increasing productivity (Ren *et al.*, 2023), mitigating climate change, promoting agricultural sustainability and ensuring food security (Wang, 2022).

5. Conclusion

In this study, we estimated the GHG emissions in tropical coffee-producing areas. The study demonstrated and quantified the main factors associated with GHG emissions. Besides, it was possible to point out how to mitigate them. These significant results furnish data and hypothesis for further studies in this segment. Therefore, some important conclusions can be drawn from this investigation: (I) the GHG emission, in kgCO_2eq per kg of coffee, ranged from 2.22 to 6.88, aligning with emissions associated with Brazilian coffee cultivation and lower than the global average for green coffee; (II) the main contributor to N_2O emissions was synthetic nitrogenous fertilizers, especially the urea-based ones and (III) in tropical areas, more studies are necessary to corroborate the effect of agricultural management practices on emission factors.

CRediT authorship contribution statement

Derielsen Brandão Santana: Conceptualization, Writing – original draft, Visualization, Methodology, Conceptualization. **Heloísa Tieghi:** Methodology, Investigation. **Guilherme da Silva Rios:** Software, Visualization. **Raissa Eduarda da Silva Archanjo:** Methodology, Investigation. **Felipe Gomes Rubira:** Formal analysis, Writing – review and editing. **Joaquim Ernesto Bernardes Ayer:** Conceptualization, Writing – review and editing, Supervision. **Paula Carolina Pires Bueno:** Writing – review and editing, Supervision, Funding acquisition. **Ronaldo Luiz Mincato:** Conceptualization, Writing – original draft, Writing – review and editing, Supervision, Project administration.

Declaration of competing interest

All the authors declare no conflict of interest.

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Figure and Table captions

Fig. 1. Coffee farms and land area covered in the present study. (A) Conquista, (B) Capoeirinha, and (C) Rio Verde.

Fig. 2. LULC maps of the farm's units covered in the present study. (A) Conquista, (B) Capoeirinha, and (C) Pinheirinho (upper map) and Rio Verde (lower map).

Fig. 3. Soil classes of the farm's units covered in the present study. (A) Conquista, (B) Capoeirinha, and (C) Rio Verde and (D) Pinheirinho.

Fig. 4. Digital elevation model (DEM) of the farm's units covered in the present study. (A) Conquista, (B) Capoeirinha, and (C) Rio Verde and (D) Pinheirinho.

Fig. 5. Electricity consumption and related GHG emissions.

Fig. 6. Data on consumption of nitrogenous fertilizers, limestone, and agricultural gypsum for the production units. (A) 2021 and (B) 2022.

Fig. 7. N_2O emissions from fertilizers. (A) 2021 and (B) 2022.

Fig. 8. Total on tCO_2 eq emissions from fertilizers. (A) 2021 and (B) 2022.

Fig. 9. Total on tCO_2 eq emissions from all sources. (A) 2021 and (B) 2022.

Fig. 10. (A) Total emission in t CO_2eq related to area for the production units in 2021 and 2022 and (B) emission per area and per production in 2021 and 2022.

Table 1. Equations used to calculate the GHG emissions in the farms included in the present study.

Table 2. Data about stationary and mobile sources at Conquista in 2021 and 2022.

Table 3. Data about stationary and mobile sources at Capoeirinha in 2021 and 2022.

Table 4. Data about stationary and mobile sources at Rio Verde in 2021 and 2022.

Fig. 1.

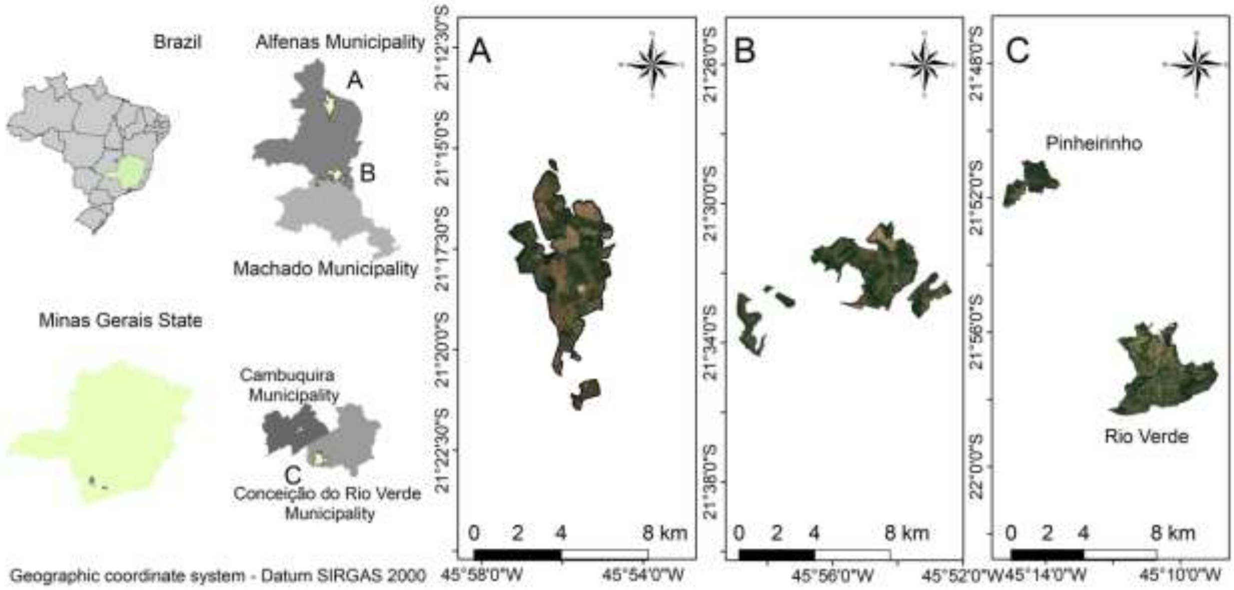
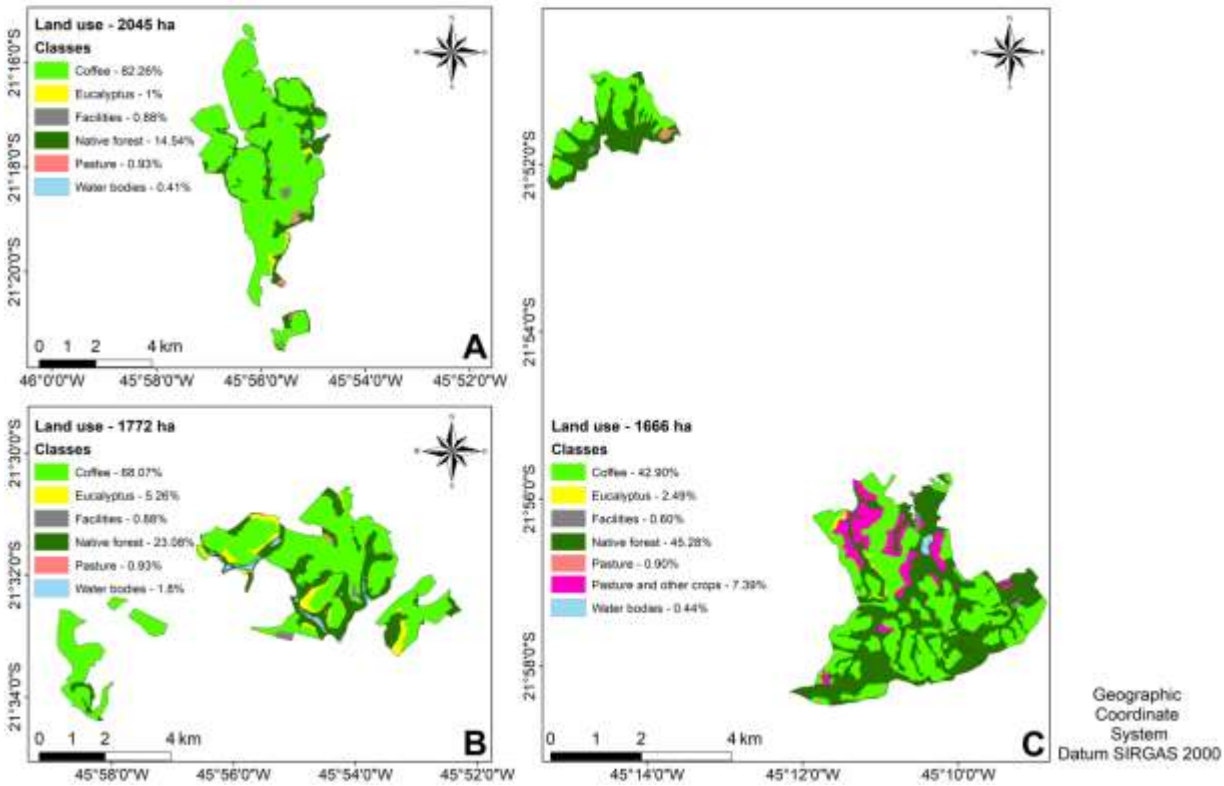

Brazil
Alfenas Municipality
A
B
Machado Municipality
Minas Gerais State
Cambuquira Municipality
C
Conceição do Rio Verde Municipality
Geographic coordinate system - Datum SIRGAS 2000
Pinheirinho
Rio Verde
0 2 4 8 km

Fig. 2.



Land use - 2045 ha
Classes
Coffee - 82.26%
Eucalyptus - 1%
Facilities - 0.88%
Native forest - 14.54%
Pasture - 0.93%
Water bodies - 0.41%
A
Land use - 1772 ha
Classes
Coffee - 68.07%
Eucalyptus - 5.26%
Facilities - 0.88%
Native forest - 23.06%
Pasture - 0.93%
Water bodies - 1.8%
B
Land use - 1666 ha
Classes
Coffee - 42.90%
Eucalyptus - 2.49%
Facilities - 0.60%
Native forest - 45.28%
Pasture - 0.90%
Pasture and other crops - 7.39%
Water bodies - 0.44%
C
0 1 2 4 km
46°0'0"W
45°58'0"W
45°56'0"W
45°54'0"W
45°52'0"W
21°16'0"S
21°18'0"S
21°20'0"S
21°30'0"S
21°32'0"S
21°34'0"S
45°14'0"W
45°12'0"W
45°10'0"W
21°52'0"S
21°54'0"S
21°56'0"S
21°58'0"S
Geographic
Coordinate
System
Datum SIRGAS 2000

Fig. 3.

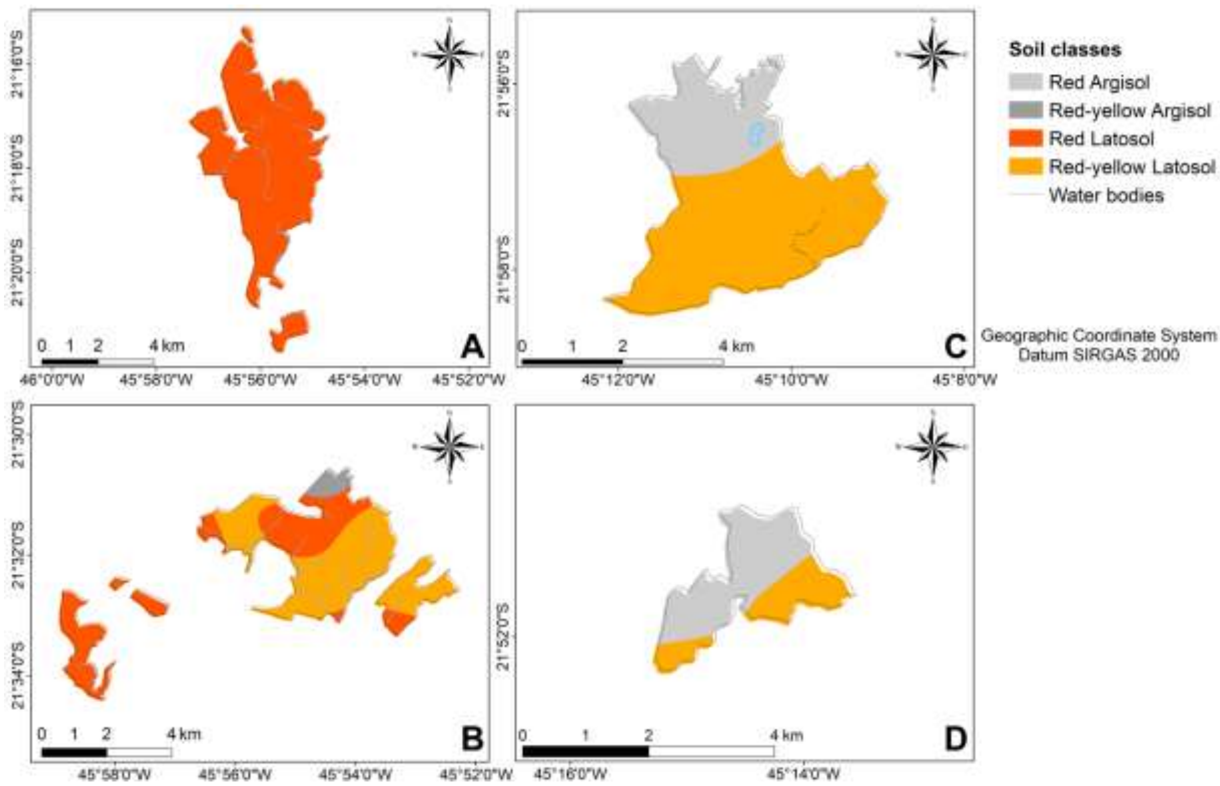

Soil classes
Red Argisol
Red-yellow Argisol
Red Latosol
Red-yellow Latosol
Water bodies
Geographic Coordinate System
Datum SIRGAS 2000
A
B
C
D
0 1 2 4 km
21°16'0"S
21°18'0"S
21°20'0"S
46°0'0"W
45°58'0"W
45°56'0"W
45°54'0"W
45°52'0"W
21°56'0"S
21°58'0"S
45°12'0"W
45°10'0"W
45°8'0"W
21°30'0"S
21°32'0"S
21°34'0"S
21°52'0"S
45°16'0"W
45°14'0"W

Fig. 4.

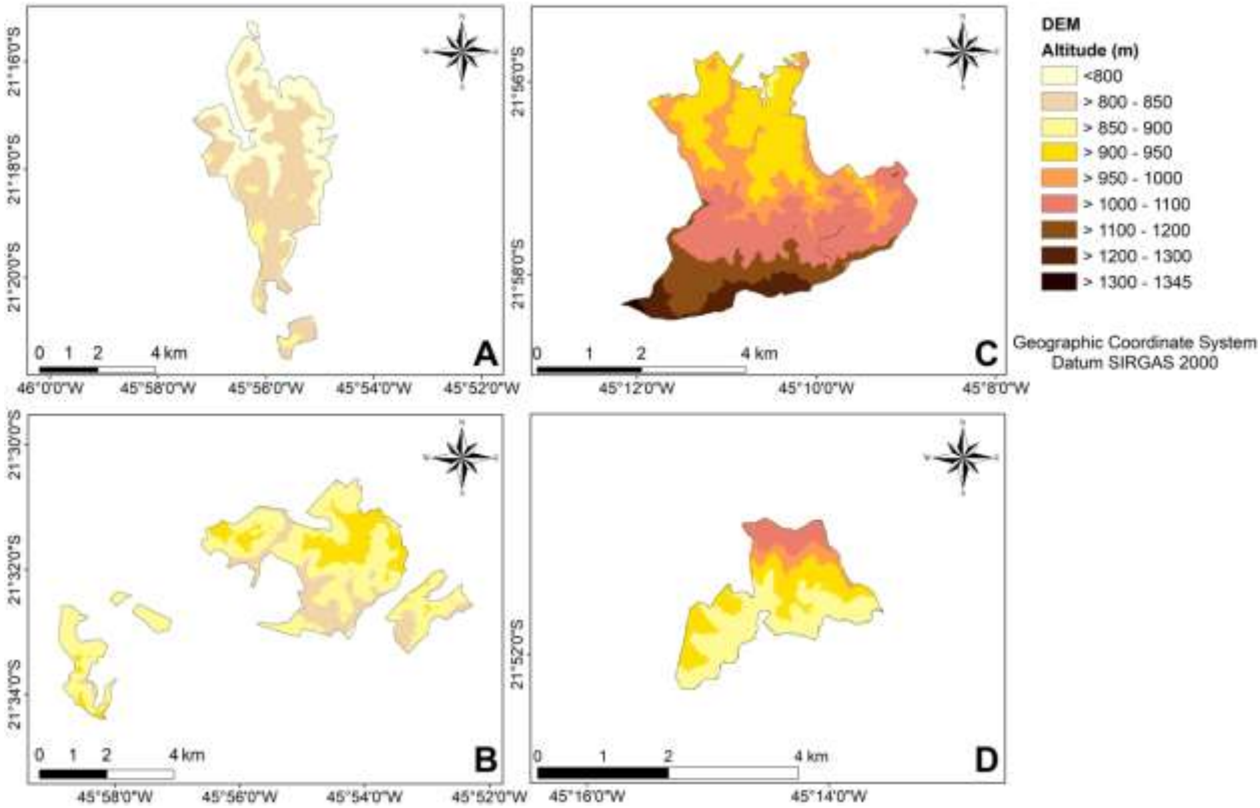

DEM
Altitude (m)
<800
> 800 - 850
> 850 - 900
> 900 - 950
> 950 - 1000
> 1000 - 1100
> 1100 - 1200
> 1200 - 1300
> 1300 - 1345
Geographic Coordinate System
Datum SIRGAS 2000
A
B
C
D
0 1 2 4 km
21°16'0"S
21°18'0"S
21°20'0"S
46°0'0"W
45°58'0"W
45°56'0"W
45°54'0"W
45°52'0"W
21°56'0"S
21°58'0"S
45°12'0"W
45°10'0"W
45°8'0"W
21°30'0"S
21°32'0"S
21°34'0"S
21°52'0"S
45°16'0"W
45°14'0"W

Fig. 5.

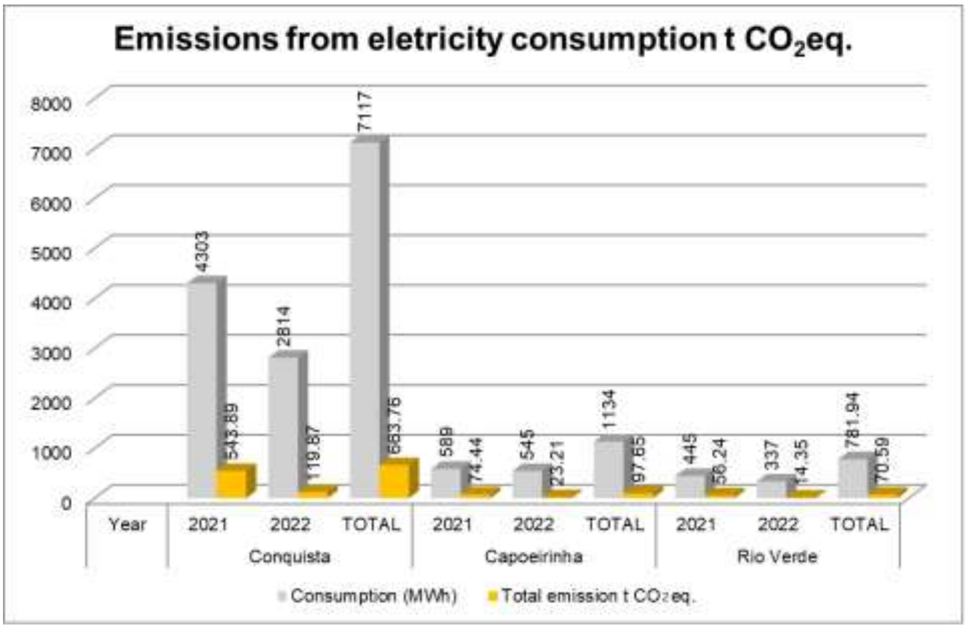
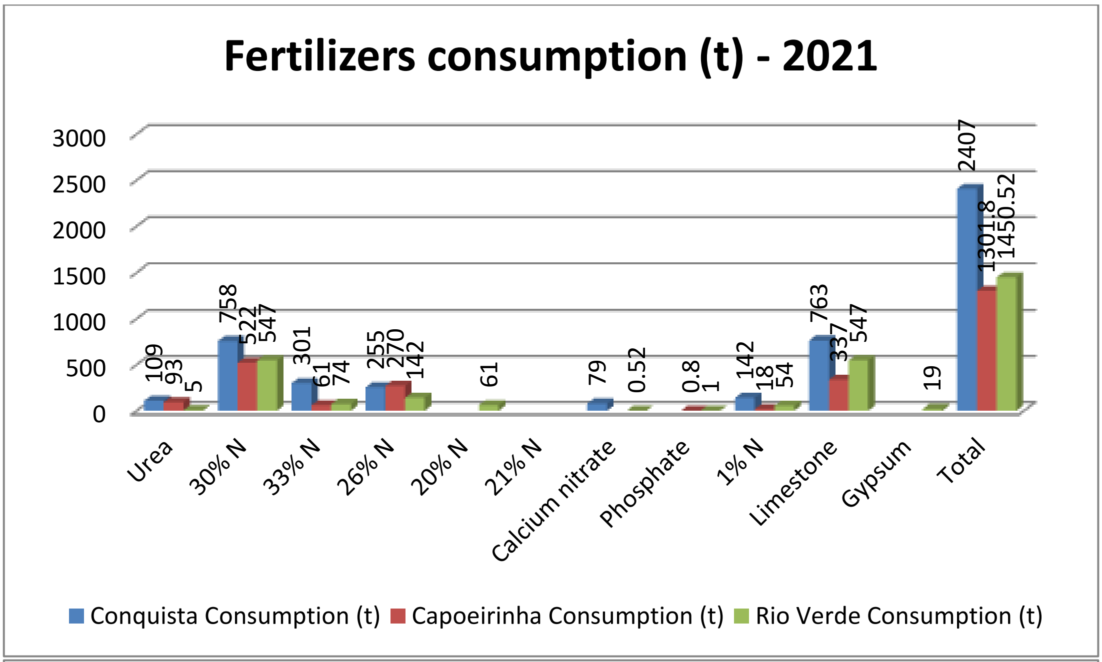

Emissions from eletricity consumption t CO2eq.
8000
7000
6000
5000
4000
3000
2000
1000
0
4303
543.89
2814
119.87
7117
663.76
589
74.44
545
23.21
1134
97.65
445
56.24
337
14.35
781.94
70.59
Year
2021
2022
TOTAL
2021
2022
TOTAL
2021
2022
TOTAL
Conquista
Capoeirinha
Rio Verde
Consumption (MWh)
Total emission t CO2 eq.

Fig. 6.


Fertilizers consumption (t) - 2021
3000
2500
2000
1500
1000
500
0
109
93
5
758
522
547
301
61
74
255
270
142
61
79
0.52
0.8
1
142
18
54
763
337
547
19
2407
1301.8
1450.52
Urea
30% N
33% N
26% N
20% N
21% N
Calcium nitrate
Phosphate
1% N
Limestone
Gypsum
Total
Conquista Consumption (t)
Capoeirinha Consumption (t)
Rio Verde Consumption (t)

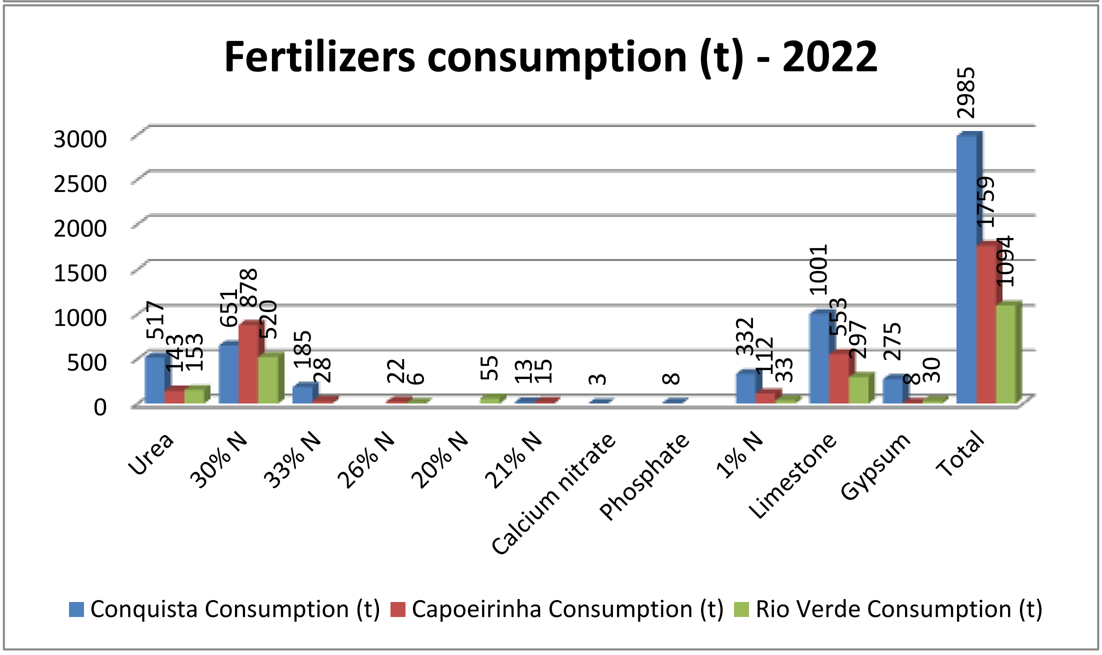

Fertilizers consumption (t) - 2022
3000
2500
2000
1500
1000
500
0
517
143
153
651
878
520
185
28
22
6
55
13
15
3
8
332
112
33
1001
553
297
275
8
30
2985
1759
1094
Urea
30% N
33% N
26% N
20% N
21% N
Calcium nitrate
Phosphate
1% N
Limestone
Gypsum
Total
Conquista Consumption (t)
Capoeirinha Consumption (t)
Rio Verde Consumption (t)

Fig. 7.

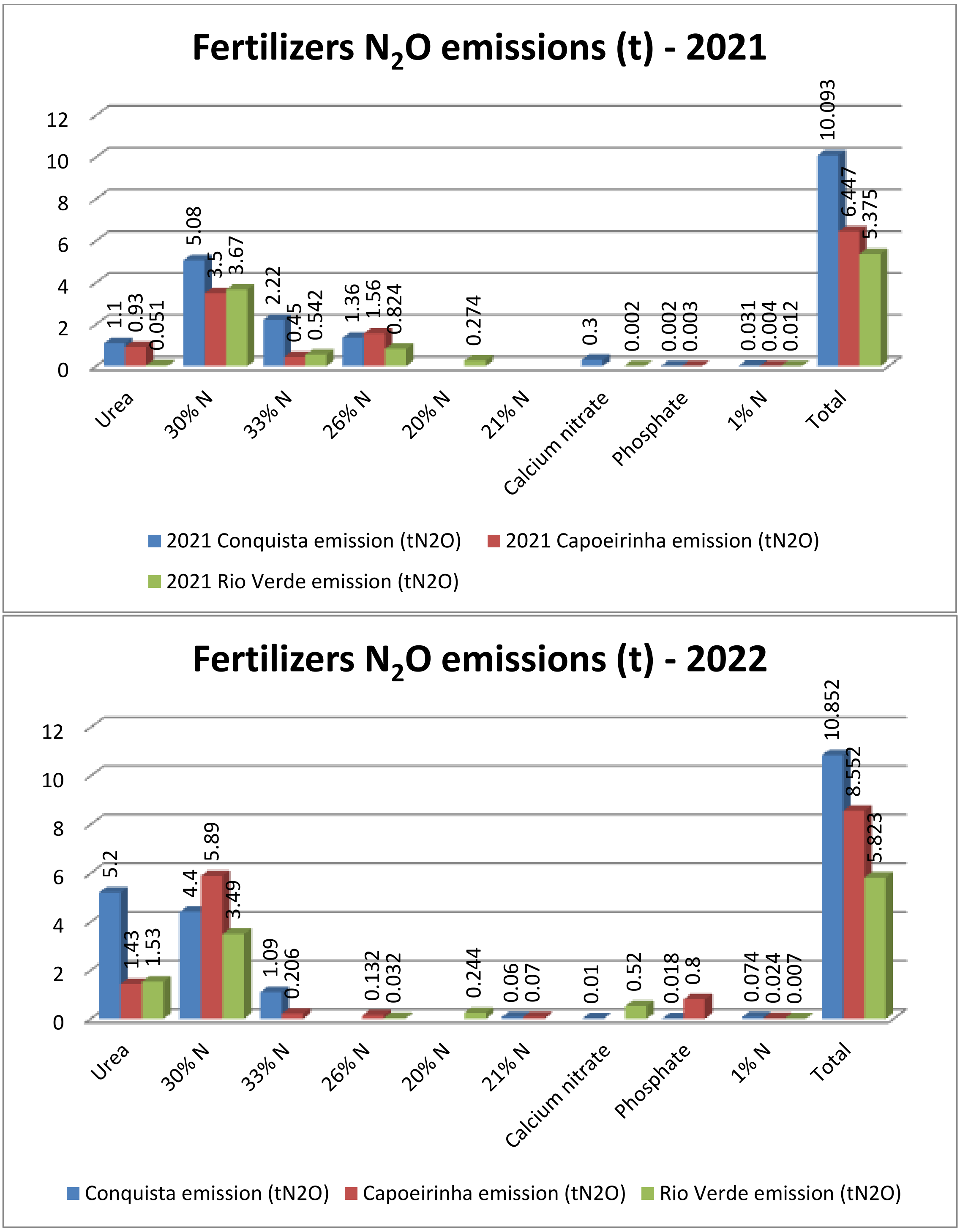
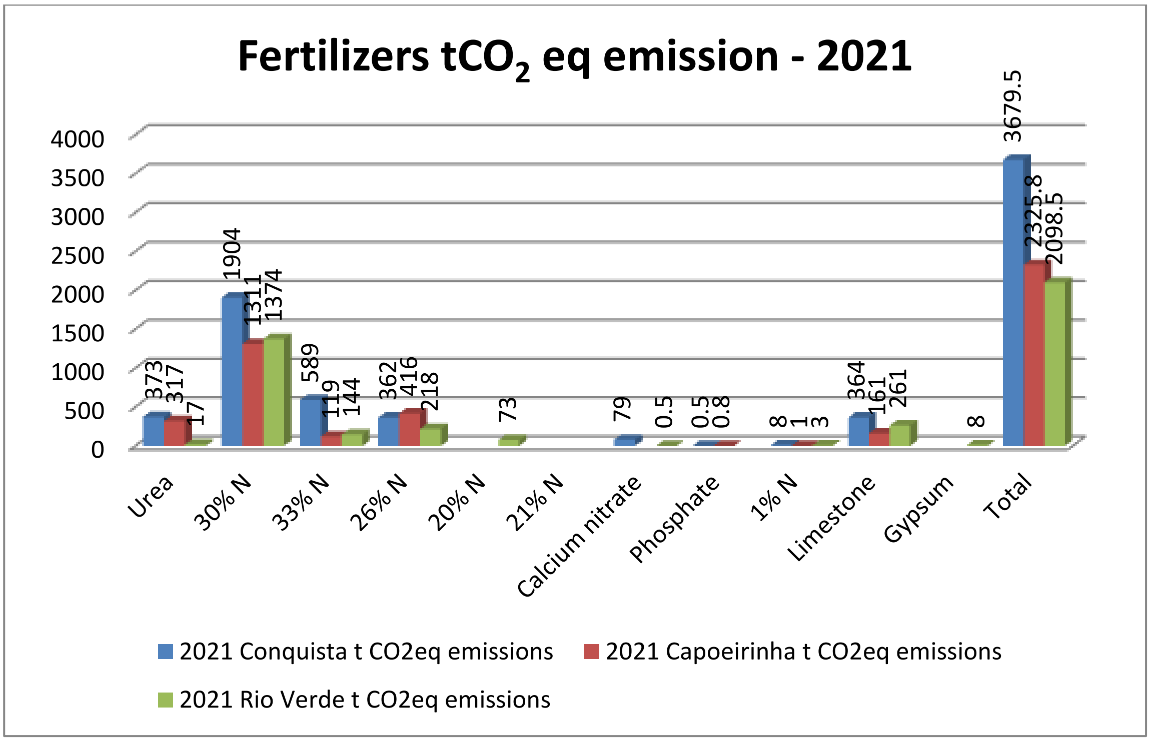
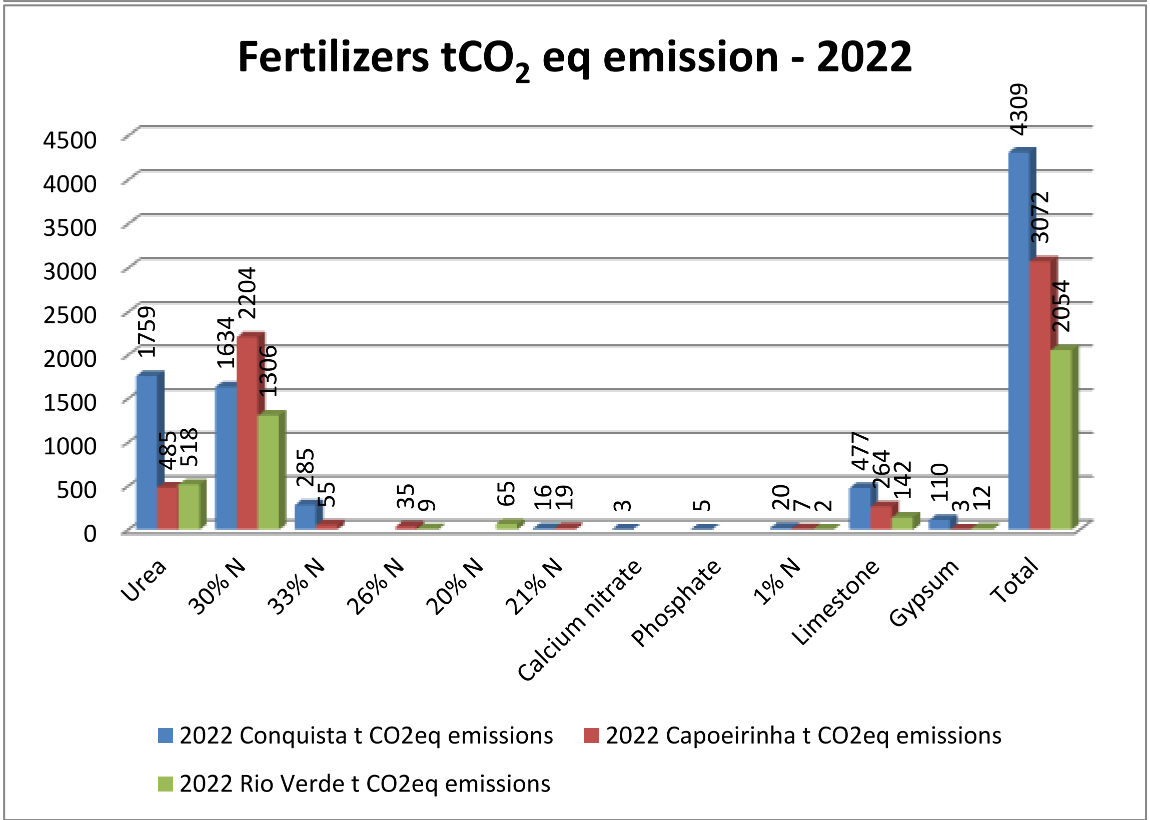

Fertilizers N_2O emissions (t) - 2021
0
2
4
6
8
10
12
1.1
0.93
0.051
5.08
3.5
3.67
2.22
0.45
0.542
1.36
1.56
0.824
0.274
0.3
0.002
0.002
0.003
0.031
0.004
0.012
10.093
6.447
5.375
Urea
30% N
33% N
26% N
20% N
21% N
Calcium nitrate
Phosphate
1% N
Total
2021 Conquista emission (tN2O)
2021 Capoeirinha emission (tN2O)
2021 Rio Verde emission (tN2O)
Fertilizers N_2O emissions (t) - 2022
0
2
4
6
8
10
12
5.2
1.43
1.53
4.4
5.89
3.49
1.09
0.206
0.132
0.032
0.244
0.06
0.07
0.01
0.52
0.018
0.8
0.074
0.024
0.007
10.852
8.552
5.823
Urea
30% N
33% N
26% N
20% N
21% N
Calcium nitrate
Phosphate
1% N
Total
Conquista emission (tN2O)
Capoeirinha emission (tN2O)
Rio Verde emission (tN2O)

Fig. 8.

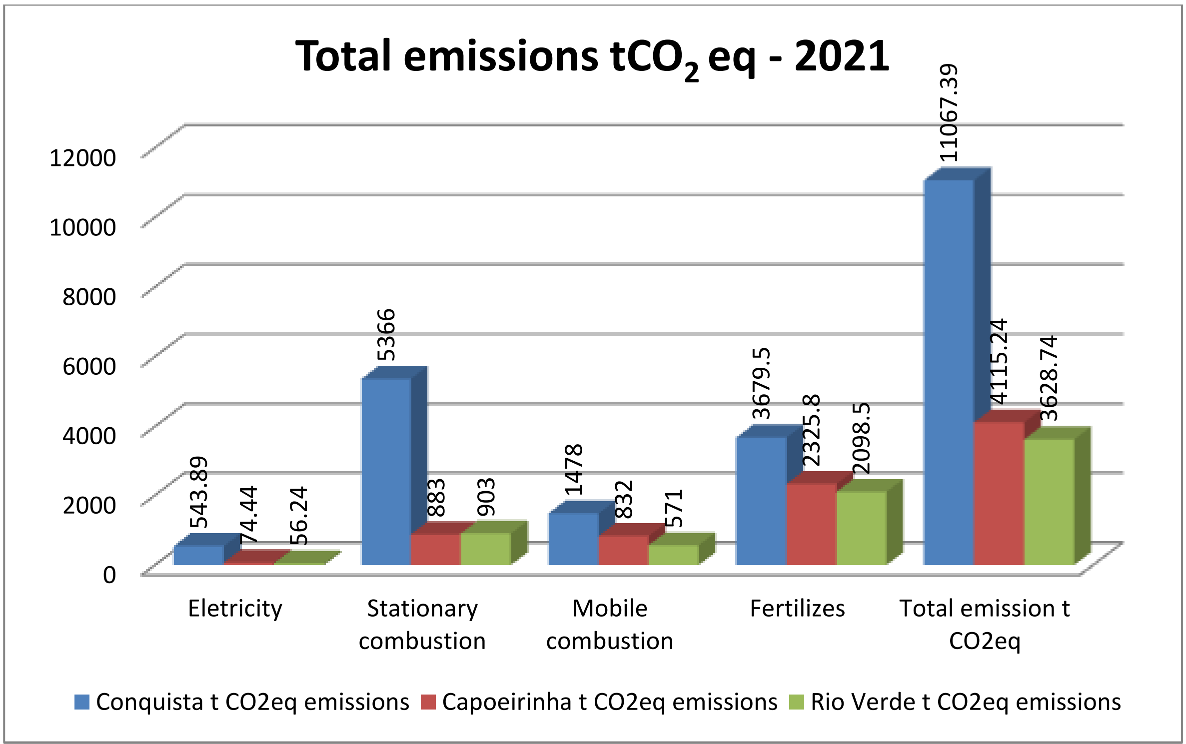


Fertilizers tCO_2 eq emission - 2021
4000
3500
3000
2500
2000
1500
1000
500
0
373
317
17
1904
1311
1374
589
119
144
362
416
218
73
79
0.5
0.5
0.8
8
1
3
364
161
261
8
3679.5
2325.8
2098.5
Urea
30% N
33% N
26% N
20% N
21% N
Calcium nitrate
Phosphate
1% N
Limestone
Gypsum
Total
2021 Conquista t CO2eq emissions
2021 Capoeirinha t CO2eq emissions
2021 Rio Verde t CO2eq emissions



Fertilizers tCO_2 eq emission - 2022
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1759
485
518
1634
2204
1306
285
55
35
9
65
16
19
3
5
20
7
2
477
264
142
110
3
12
4309
3072
2054
Urea
30% N
33% N
26% N
20% N
21% N
Calcium nitrate
Phosphate
1% N
Limestone
Gypsum
Total
2022 Conquista t CO2eq emissions
2022 Capoeirinha t CO2eq emissions
2022 Rio Verde t CO2eq emissions

Fig. 9.


Total emissions tCO_2 eq - 2021
12000
10000
8000
6000
4000
2000
0
543.89
74.44
56.24
5366
883
903
1478
832
571
3679.5
2325.8
2098.5
11067.39
4115.24
3628.74
Eletricity
Stationary combustion
Mobile combustion
Fertilizes
Total emission t CO2eq
Conquista t CO2eq emissions
Capoeirinha t CO2eq emissions
Rio Verde t CO2eq emissions

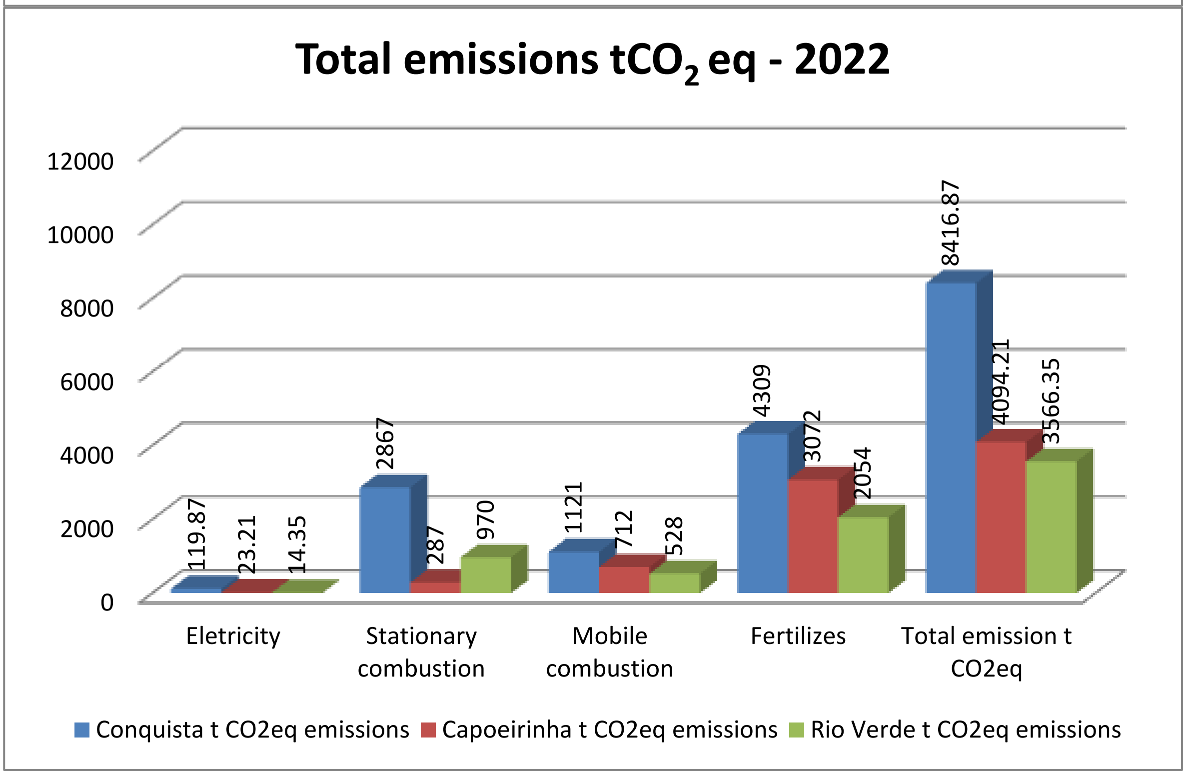

Total emissions tCO_2 eq - 2022
12000
10000
8000
6000
4000
2000
0
119.87
23.21
14.35
2867
287
970
1121
712
528
4309
3072
2054
8416.87
4094.21
3566.35
Eletricity
Stationary combustion
Mobile combustion
Fertilizes
Total emission t CO2eq
Conquista t CO2eq emissions
Capoeirinha t CO2eq emissions
Rio Verde t CO2eq emissions

Fig. 10.

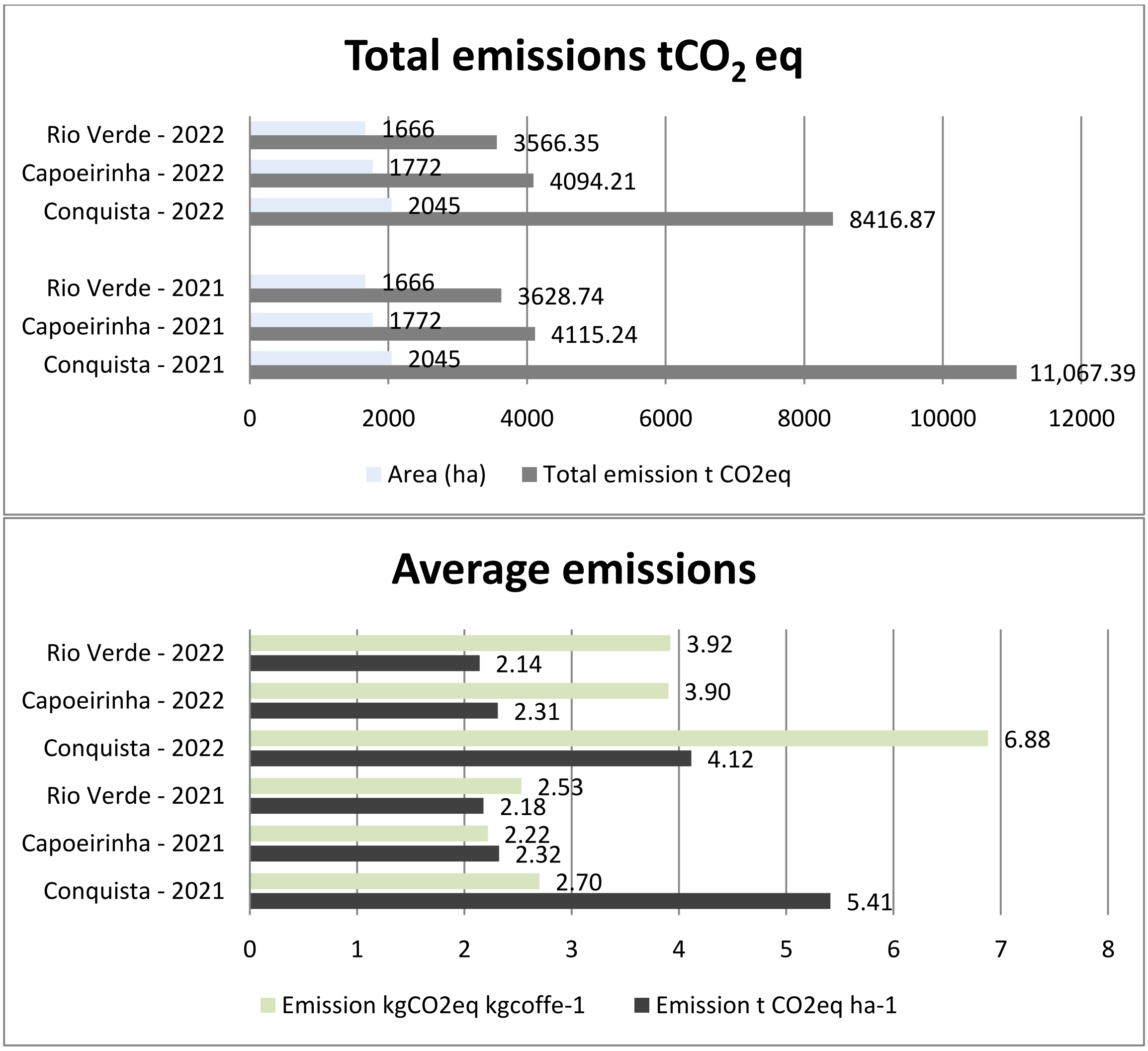

Total emissions tCO_2 eq
Rio Verde - 2022
Capoeirinha - 2022
Conquista - 2022
Rio Verde - 2021
Capoeirinha - 2021
Conquista - 2021
1666
3566.35
1772
4094.21
2045
8416.87
1666
3628.74
1772
4115.24
2045
11,067.39
0
2000
4000
6000
8000
10000
12000
Area (ha)
Total emission t CO2eq
Average emissions
Rio Verde - 2022
Capoeirinha - 2022
Conquista - 2022
Rio Verde - 2021
Capoeirinha - 2021
Conquista - 2021
3.92
2.14
3.90
2.31
6.88
4.12
2.53
2.18
2.22
2.32
2.70
5.41
0
1
2
3
4
5
6
7
8
Emission kgCO2eq kgcoffe-1
Emission t CO2eq ha-1

Table 1. Equations used to calculate the GHG emissions in the farms included in the present study.

Eq.	Meaning	Equation	Variables
1	Electricity emissions	$CO_2eq = EE \times EF$	CO_2eq = carbon dioxide equivalent emissio EE = electricity consumption EF = emission factor
2	Emissions from fossil fuels	$CO_2 = FF \times EF$	CO_2= carbon dioxide direct emissions FF = Consumption of fossil fuels EF = emission factor
3	Emissions from wood and vegetable waste burning	$CO_2 = BW \times EF$ or $CO_2 = VR \times EF$	BW = burning wood consumption VR = burning waste vegetable EF = emission factor
4	Emissions of N_2O from nitrogenous fertilizers	$EN_2O = N_{fert} \times EF$	EN_2O = nitrous oxide emissions N_{fert} = amount of N applied EF = emission factor
5	Direct emission of CO_2 from urea-based nitrogenous fertilizers	$CO_{2urea} = M_{urea} \times EF_{urea}$	CO_{2urea}= direct CO_2 emission from urea M_{urea} = amount of urea EF_{urea}= urea emission factor
6	Emissions from limestone	$CO_{2lim.} = M_{lim.} \times EF_{lim.}$	$CO_{2lim.}$ = limestone emissions $M_{lim.}$ = amount of limestone $EF_{lim.}$ = emission factor
7	Emissions from LPG	$CO_2 = LPG \times EF$	LPG = amount of LPG EF = emission factor
8	Conversion of N_2O to CO_2eq	$CO_2eq = EN_2O \times 265$	EN_2O = nitrous oxide emissions
9	Conversion of CH_4 to CO_2eq	$CO_2eq = ECH_4 \times 28$	ECH_4 = methane emissions

Table 2. Data about stationary and mobile sources at Conquista in 2021 and 2022.

Conquista – Stationary combustion						
	2021			2022		
Source	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic emissions (tCO_2)	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic emissions (tCO_2)
Wood burning	1588.00	271.71	2885.62	1313.00	224.69	2385.91
Vegetable waste	1628.00	178.65	1890.37	194.00	21.29	225.27
Diesel	46,798.00	123.93	-	3479.00	9.22	-
Biodiesel	5881.00	-	14.50	437.50	-	1.07
Total	55,895.00	574.29	4790.49	5423.50	255.20	2612.25
Conquista – Mobile combustion						
	2021			2022		
Source	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic emissions (tCO_2)	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic emissions (tCO_2)
Diesel	448,189.00	1185.00	-	322,968.00	854.38	-
Biodiesel	56,339.00	-	137.00	39,889.00	-	96.97
Gasoline	50,697.00	225.00	-	38,014.00	87.69	-
Ethanol	18,751.00	-	28.00	14,060.00	-	21.46
LPG	10.37	3.00	-	20,183.00	60.86	-
Total	573,986.37	1413.00	165.00	434,844.00	1002.93	118.43

Table 3. Data about stationary and mobile sources at Capoeirinha in 2021 and 2022.

	Capoeirinha – Stationary combustion					
	2021			2022		
	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic emissions (tCO_2)	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic er (tCO_2)
rning	444.00	76.00	807.00	144.00	24.64	261.67
	444.00	76.00	807.00	144.00	24.64	261.67

	Capoeirinha – Mobile combustion					
	2021			2022		
	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic emissions (tCO_2)	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic er (tCO_2)
	275,688.00	734.00	-	234,641.00	620.71	-
	34,655.00	-	82.00	28,828.00	-	70.08
	5747.00	13.00	-	7687.00	17.73	-
	2126.00	-	3.00	2843.00	-	4.34
	318,216.00	747.00	85.00	273,999.00	638.44	74.42

Table 4. Data about stationary and mobile sources at Rio Verde in 2021 and 2022.

	Capoeirinha – Stationary combustion					
	2021			2022		
	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic emissions (tCO_2)	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic en (tCO_2)
rning	454.00	78.20	825.00	488.00	83.50	887.00
	454.00	78.20	825.00	488.00	83.50	887.00

	Capoeirinha – Mobile combustion					
	2021			2022		
	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic emissions (tCO_2)	Consumption (t) - (L)	Direct emissions (tCO_2)	Biogenic en (tCO_2)
	152,415.00	403.20	-	142,541.00	377.00	-
	19,159.00	-	47.00	17,918.00	-	43.56
	40,706.00	93.90	-	32,323.00	74.50	-
	15,055.00	-	23.00	11,955.00	-	18.24
	1230.00	3.71	-	4600.00	13.87	-
	228,565.00	500.81	70.00	209,337.00	465.37	61.80

6 FINAL CONSIDERATIONS

The largest GHG emissions come from the use of nitrogen fertilizers, since the N_2O emission factor is high, especially urea products that contain C in their formulation;

The Conquista Unit generates more total GHG emissions because it is responsible for the flow of production, consumes more fossil fuels, firewood, electricity and fertilizers, and also produces a larger quantity of coffee; however, C removal is also higher, ranging from -5.99 to -9.12 tCO_2e/ha;

The farms can be considered C sinks, since they are removing C from the atmosphere. This condition is associated with agricultural management for coffee production, maintenance of native forests, frequent pruning and reduction in the use of direct firewood;

The C stock in the coffee areas is within the standard values for coffee growing in Minas Gerais, demonstrating the relevance of this practice in maintaining the biogeochemical cycles of global CO_2;

Further studies are needed to improve the precision and accuracy of the results, such as the amount of organic matter and fertilizers used in each coffee plot, the correct year of planting and pruning, and the C stocks of all land uses and occupations measured in the field;

The Inventory has proven to be an essential tool for quantifying GHG emissions in the production chain, allowing for increasingly efficient management of agriculture. Furthermore, in the current context, it is an essential tool for seeking carbon certifications, complying with environmental regulations, and accessing carbon credit markets, strengthening competitiveness and environmental responsibility for the sake of a better world.

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ATTACHMENTS – METHODOLOGICAL DATA COLLECTION AND RESULTS

GHG emissions/removals were calculated using Microsoft Excel spreadsheets, divided according to production units (Rio Verde, Conquista and Capoeirinha) for the years 2021, 2022 and 2023. Regarding 2024, some data were not available, so it was decided not to carry out the inventory.

GHG sources followed the GHG Protocol model, categorized into scopes 1, 2 and 3. The gases were divided into carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), all of which were converted to carbon dioxide equivalent (CO_2e.), adopting GWP-100 AR6 (IPCC, 2021). This process was carried out according to the equations obtained from the literature adopted in the IPCC manuals (2006, 2019) and in the updated technical notes of the FGV adapted for Brazil (FGV, 2022; 2023). The input data for the equations were recorded as provided by Ipanema Coffees.

Emissions/removals were also categorized as biogenic and non-biogenic. Biogenic emissions are those related to the natural carbon cycle, such as those resulting from combustion, harvesting, digestion, fermentation, removal by plants, decomposition or processing of bio-based materials, such as the burning of biofuels and plant biomass and the aerobic decomposition of organic matter (IPCC, 2006). Non-biogenic emissions are those from fossil fuels and non-renewable sources.

Below are described the equations used and organized according to scope:

1.1 SCOPE 1:

• CO_2 Emissions from stationary combustion (diesel, gasoline, firewood and plant waste) and mobile combustion (diesel, gasoline and LPG):

$$\mathrm{ECO_2} = \mathrm{Q} \times \mathrm{EF} \tag{2}$$

Where:
ECO_2 is the CO_2 emission associated with stationary/mobile combustion (kg CO_2e.);
Q is the quantity of material consumed (kg/t or L);
EF is the emission factor (kg CO_2/un), where un = kg or L.

The emission factors for stationary/mobile combustion are shown in Table 2:

Table 2 – emission factors for stationary and mobile combustion

Stationary combustion						
Emission factor – fossil fuels				Emission factor – bio fuels		
Source	kg CO_2/un	kg CH_4/un	kg N_2O/un	kg CO_2/un	kg CH_4/un	kg N_2O/un

Diesel	2.60	0.00036	0.00002	2.46	0.00033	0.00002
Gasoline	2.24	0.00032	0.00002	1.58	0.00022	0.00001
Firewood	-	-	-	1451.50	3.89	0.05
Vegetal waste*	-	-	-	1161.16	3.48	0.05
Mobile combustion						
Emission factor – fossil fuels				Emission factor – bio fuels		
Source	kg CO_2/un	kg CH_4/un	kg N_2O/un	kg CO_2/un	kg CH_4/un	kg N_2O/un
Diesel	2.60	0.00036	0.00002	2.43	0.00033	0.00002
Gasoline	2.21	0.00032	0.00002	1.53	0.00022	0.00001
LPG	2.93	0.23237	0.00465	-	-	-

*coffee husk and shell

• N_2O emissions from the use of synthetic nitrogen fertilizers:

$$EN_2O = N_{fert} \times EF \quad (3)$$

Where:
EN_2O are the N_2O emissions (in kg of N_2O) resulting from the use of synthetic nitrogen fertilizer;
N_{fert} is the amount of N applied as nitrogen fertilizer (in kg of N);
EF is the emission factor (in kg of N_2O/kg N) (MCTI, 2020), equivalent to 0.02235.

The suggested Emission Factor (0.02235 kg N_2O/kg N) was obtained from the data reported in the Reference Report of the Fourth National Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases (MCTI, 2020). This already considers direct and indirect emissions of N_2O resulting from the use of synthetic fertilizers.

• CO_2 emissions from the use of agricultural limestone and gypsum:

$$ECO_{2calc} = M \times EF_{lim} \quad (4)$$

Where:
ECO_{2calc} is the CO_2 emissions (in kg of CO_2) resulting from the use of limestone and agricultural gypsum;
M is the quantity of limestone and agricultural gypsum applied (in kg);
EF_{lim} is the emission factor (in kg of CO_2/kg limestone and gypsum) used in the Fourth National Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases (MCTI, 2020), equivalent to 0.4767 for limestone and 0.4 for agricultural gypsum.

• CO_2 emissions from the application of urea fertilizers:

$$ECO_{2urea} = M \times EF_{urea} \quad (5)$$

Where:
ECO_{2urea} are the direct CO_2 emissions (in kg of CO_2) resulting from the application of fertilizers containing urea;
M is the amount of fertilizer applied (in kg);
EF_{urea} is the emission factor (in kg of CO_2/kg urea) used in the Fourth National Inventory of Anthropogenic Emissions and Removals of Greenhouse Gases (MCTI, 2020), equivalent to 0.7333.

• N_2O emissions from the use of organic nitrogen fertilizers:

$$N_2O_{AD.ORG} = Q_{ORG} \times N_{AD}\ (1 - FRAC_{GASM}) \times EF \times 44/28 \qquad (6)$$

Where:
$N_2O_{AD.ORG}$ are the N_2O emissions (in kg of N_2O) resulting from the application of organic nitrogen fertilizers;
Q_{ORG} is the amount of organic fertilizer applied (in kg);
N_{AD} is the percentage of nitrogen in the organic fertilizer (%) (1.4) (KIEHL, 1985; LOPES, 1989);
$FRAC_{GASM}$ is the fraction of the applied N that volatilizes in the form of NH_3 and NO_x (%) (0.2) (IPCC, 2006);
EF is the emission factor (%) (0.01) (MCT, 2010);
44/28 is the conversion of N-N_2O to N_2O.

• CO_2 removals from aboveground biomass:

For CO_2 removals, the GHG Forestry Brazil (FGV, 2021) methodology adapted from the IPCC (2006) was used:

$$CO_2 = [(A \times Plants \times Tcbiomass \times d \times c\% \times 44/12) / 1000] \times fpruning^* \qquad (8)$$

Where:
CO_2 = C removal, converted to CO_2 equivalent (t CO_2/year);
A = area (ha);
Plants = estimated number of plants/ha (dimensionless), determined by Ipanema Coffees;
Tcbiomass = annual biomass growth rate (m³/plant/year);
d = density (kg/m³);
c% = C in biomass (%);
44/12 = conversion constant of C to CO_2e (3.66...) (dimensionless);
1000 = conversion of kg to t (dimensionless);
fpruning = fraction of biomass lost in annual coffee pruning (0.6).

The Tcbiomass used was 0.005 m3/plant/year for coffee (Matiello *et al.*, 2016), 0.025 for eucalyptus (IPCC, 2019) and 0.024 for native forest (IPCC, 2019). The density (d) of the wood used was 0.62 for coffee (INCAPER, 2018; IPCC, 2019), 0.51 for eucalyptus (EMBRAPA, 2019) and 0.67 for forest (IPCC, 2019). The C content (c%) in the biomass was used according to the IPCC (2019) and Oliveira Junior *et al.* (2022), 0.44 for coffee and 0.47 for eucalyptus and forest. For C removal, annual pruning was considered to avoid overestimating values. Due to the lack of some data for each coffee plot, the 15-year longevity of plants with linear growth was chosen (IPCC, 2006). Plants over 15 years old were disregarded in the calculation of annual C removal.

• CO_2e emissions from liquid effluent treatment

$$CO_{2WT} = (N \times BOD \times DW \times Bo \times MCF \times 27) / 10^6 \quad (9)$$

Where:
CO_{2WT} = CO_2e emissions (already converted) from liquid effluent treatment (t CO_2e);

N = number of employees in the organization, usually calculated monthly (dimensionless);
BOD = BOD load per person per day (g/person/day);
DW = days worked per month (every 3 days worked = 1 DW, considering a workload of 8 hours);
BO = CH_4 production capacity (kg CH_4 / kg BOD);
MCF = CH_4 conversion factor (0.5);
27 = GWP of CH_4 no fossil;
10^6 = conversion from g to t.

BOD, Bo and MCF were obtained from MCT and IPCC (2006).

• CO_2 stock in soil under coffee cultivation

$$EST.CO_2 = [(CO \times Ds \times e) / 10] \times 44/12 \quad (10)$$

Where:
$EST.CO_2$ = soil C stock already converted to CO_2 for a given depth;
CO = organic carbon content at the sampled depth according to collection (g / kg);
Ds = soil density at the sampled depth (kg / dm^3);
e = soil thickness;
44/12 = conversion of C to CO_2.

To calculate the soil C stock, 46 soil samples were collected from the coffee plots, as shown in Figure 3, one per plot, in January 2021, 2022 and 2023. These samples weighed approximately 600 g and were collected at a depth of 0 to 20 cm. Organic matter (OM) was determined by Cooxupé laboratories using the dry quantification methodology in a muffle furnace via incineration (Santos *et al.*, 2018). The C content was subsequently calculated by dividing the OM content by 1.724 (USDA; NRCS, 1996). After obtaining the C, it was multiplied by 3.66 (44/12) to calculate the CO_2 stock of each plot. An average density for the cultivation areas (1.22) was considered, with a thickness of 20 cm. The inventory for forest areas, eucalyptus and other crops was not carried out due to insufficient data.

1.2 SCOPE 2:

• CO_2 emissions from electricity consumption based on location:

$$CO_{2EE} = EE \times EF \quad (11)$$

Where:
CO_{2EE} is the CO_2 emission from electricity consumption (t CO_2);
EE is the electricity consumption (MWh);
FE is the national emission factor (t CO_2/MWh), which varies annually, obtained from MCTI.

1.3 SCOPE 3:

• CO_2e emissions (t) from the treatment of solid waste generated:

$$CO_2e = MWT \times MCF \times DOC \times DOCf \times F \times (1 - O_X) \times 16/12 \times 27 \quad (12)$$

Where:
CO_2e = total CO_2e emissions (t);
MWT = mass of solid waste deposited in the landfill (kg);
MCF = methane correction factor (0.6 semi-managed landfills), depending on the type of landfill (FGV, 2020);
DOC = degradable organic carbon content of the waste (0.15) (kg C/kg waste) (IPCC, 2006);
DOCf = fraction of degradable organic carbon that decomposes (0.5) (dimensionless) (IPCC, 2006);
F = fraction of biogas that is methane (0.5) (dimensionless) (IPCC, 2006);
O_X = methane oxidation factor (0.1) (dimensionless) (IPCC, 2006);
16/12 = carbon to methane conversion factor;
27 = GWP of CH_4.

First, it is necessary to calculate the total degradable organic carbon (DOCT) (kg), according to equation 13:

$$DOC_T = M_{WT} \times DOC \times DOC_f \quad (13)$$

Where:
DOC_T = total degradable organic carbon (kg);

The second step consists of calculating the initial methane generated (kg) by carbon conversion, according to equation 14:

$$CH_{4I} = DOCtotal \times 16/12 \quad (14)$$

Where:
CH_{4I} = initial CH_4 emissions (kg)

The third step consists of inserting new parameters to calculate the final CH4 emissions (kg) due to the landfill characteristics, according to equation 15:

$$CH_{4F} = CH_{4I} \times MWT \times F \times (1 – O_X) \quad (15)$$

Where:
CH_{4F} = final CH_4 emissions (kg)

The last step is to convert kg/CH_{4F} to t/CO_2e, according to equation 16:

$$CO_2e = (CH_{4F} \times 27) / 1000 \quad (16)$$

Where:
CO_2e = emissions converted to CO_2e (t)

The results are listed in general terms below:

2.1 SCOPE 1 - SYNTHETIC AND ORGANIC NITROGEN FERTILIZERS, LIMESTONE AND AGRICULTURAL GYPSUM

The 2021 emissions and consumption are shown in Figures 2, 3 and 4, categorized for each production unit.

Figure 2 - Emission and consumption from synthetic, organic and limestone nitrogen fertilizers in 2021 at the Conquista Unit

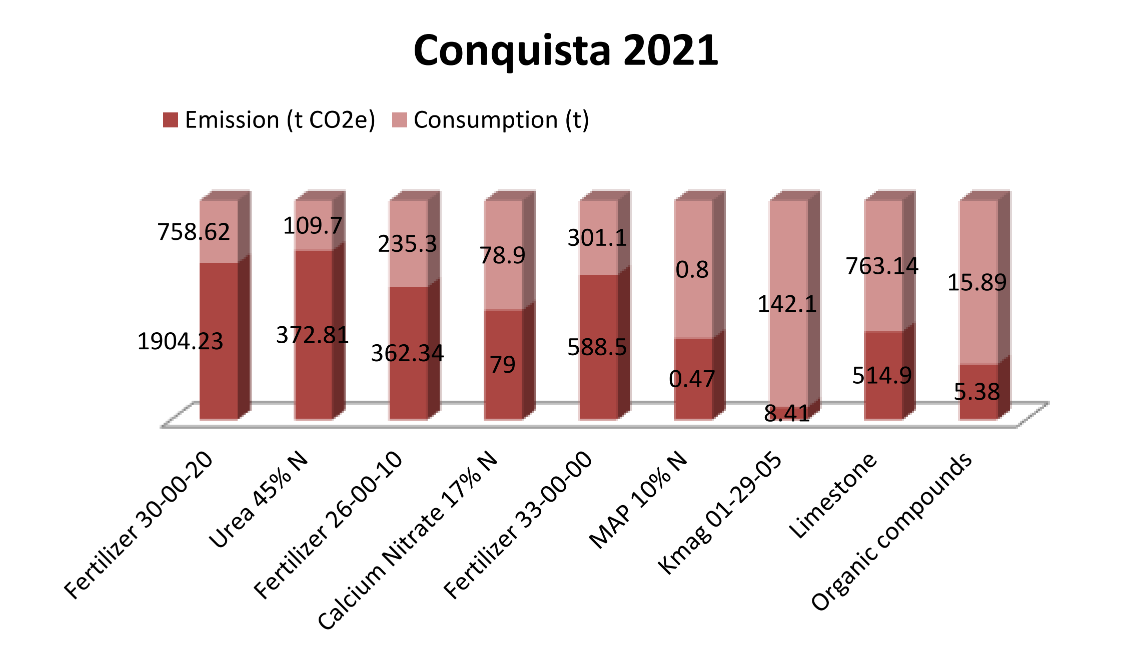


Figure 3 - Emission and consumption from synthetic, organic and limestone nitrogen fertilizers in 2021 at the Capoeirinha Unit

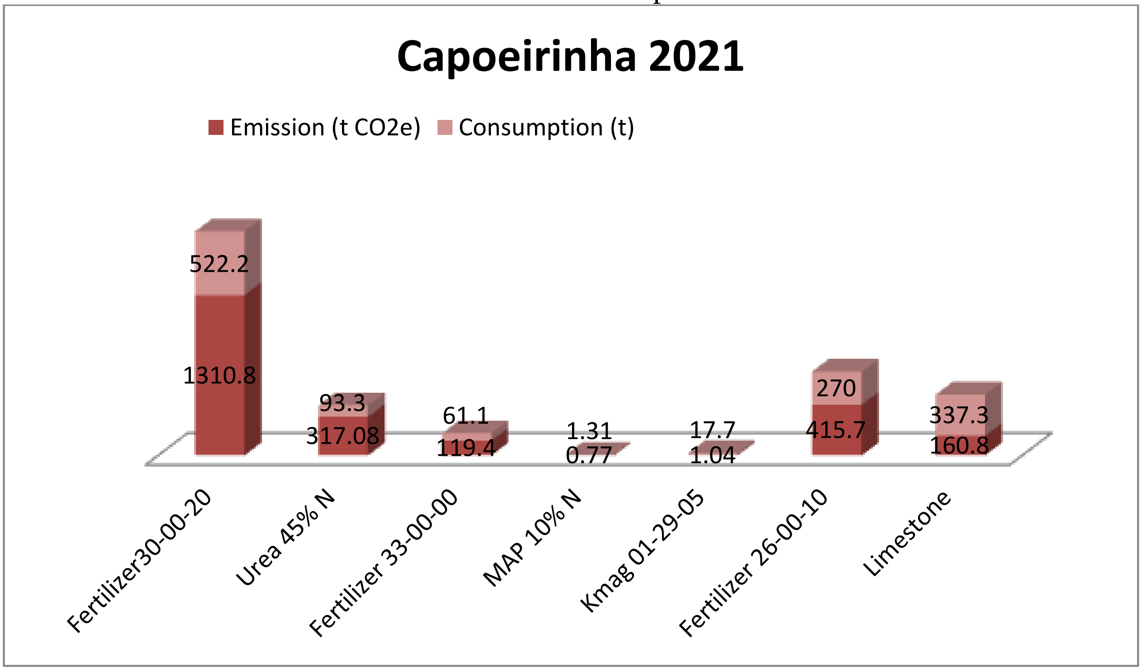
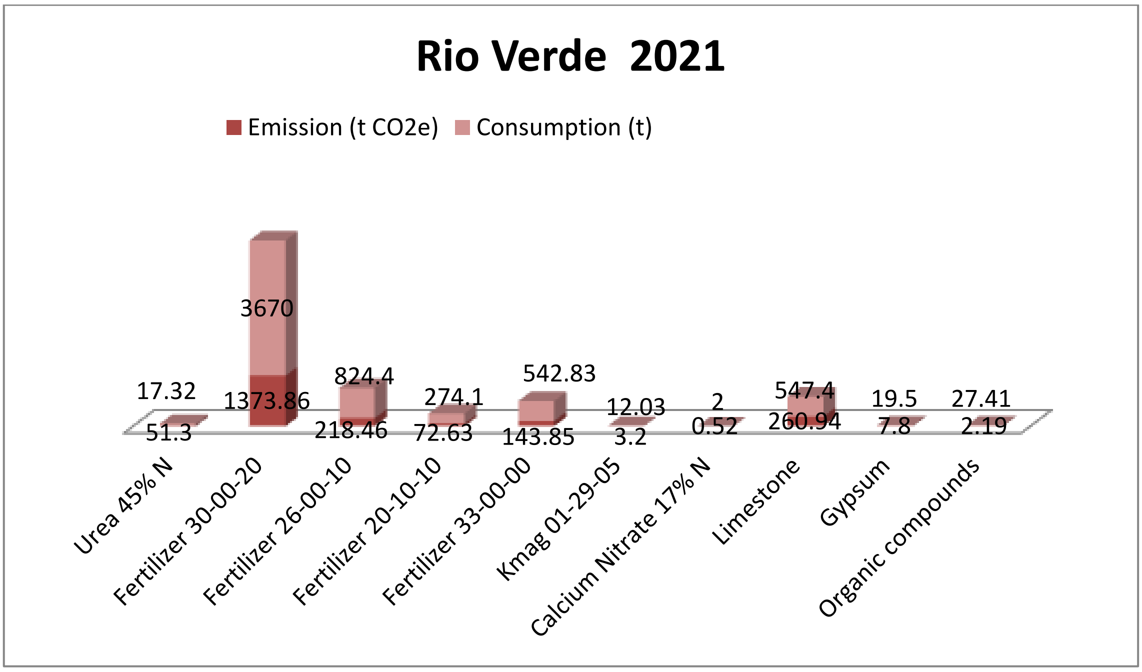


Figure 4 - Emission and consumption from synthetic, organic and limestone nitrogen fertilizers in 2021 at the Rio Verde Unit



The figures 5, 6 and 7 show emissions from synthetic nitrogen fertilizers, urea, dolomitic limestone, organic compounds and gypsum for production units in 2022.

Figure 5 - Emissions from synthetic and organic nitrogen fertilizers, limestone and agricultural gypsum in 2022 at the Conquista Unit

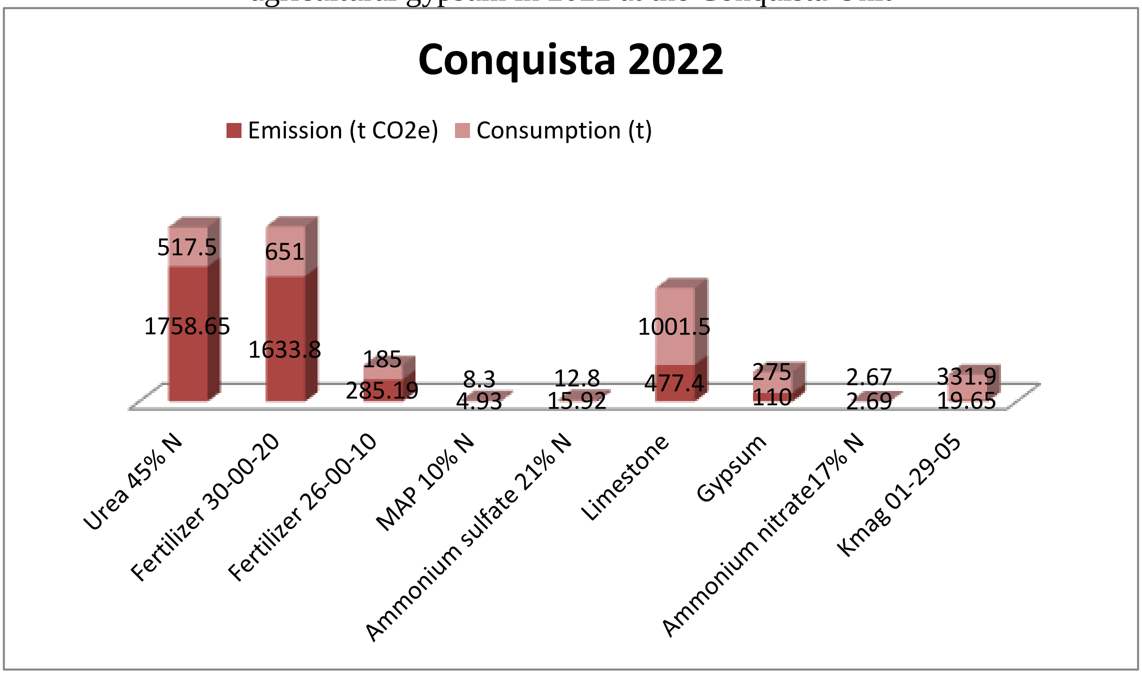


Figure 6 - Emissions from synthetic and organic nitrogen fertilizers, limestone and agricultural gypsum in 2022 at the Capoeirinha Unit

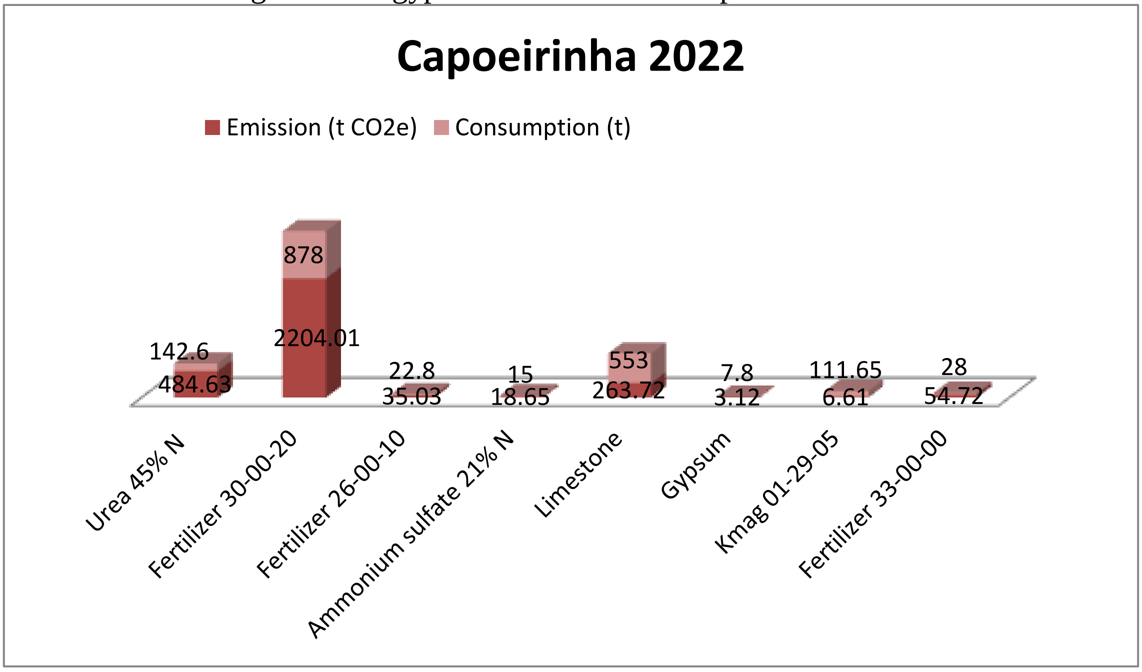
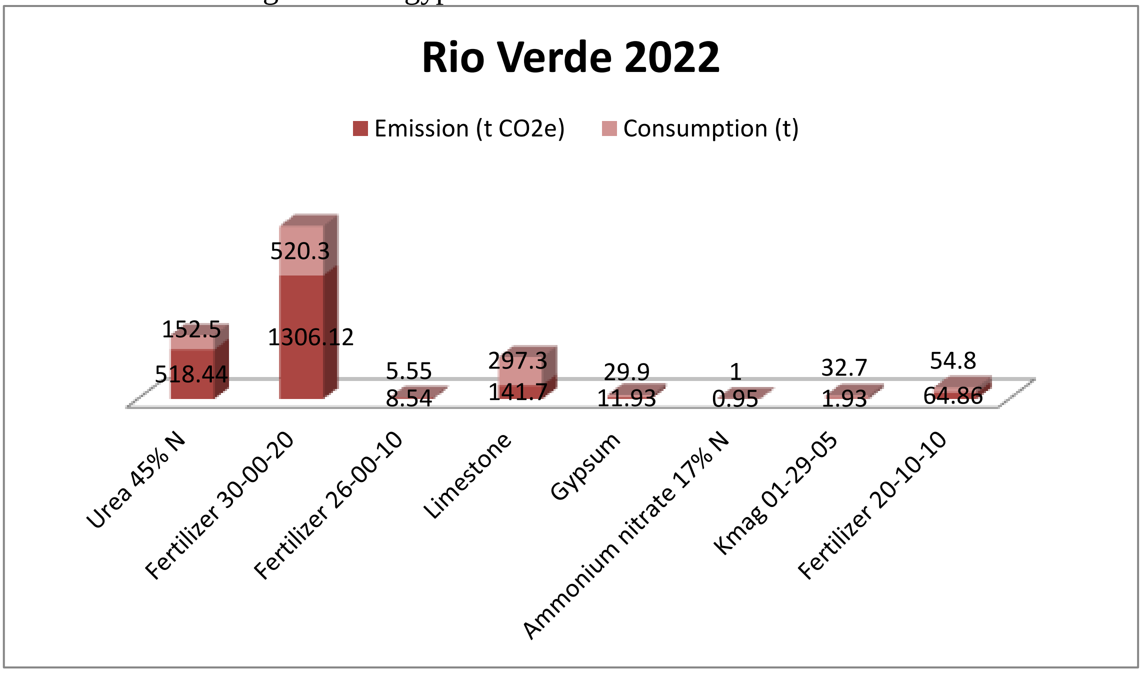


Figure 7 - Emissions from synthetic and organic nitrogen fertilizers, limestone and agricultural gypsum in 2022 at the Rio Verde Unit



The figures 8, 9 and 10 show emissions from synthetic nitrogen fertilizers, urea, dolomitic limestone, organic compounds and gypsum for production units in 2023.

Figure 8 - Emissions from synthetic and organic nitrogen fertilizers, limestone and agricultural gypsum in 2023 at the Conquista Unit

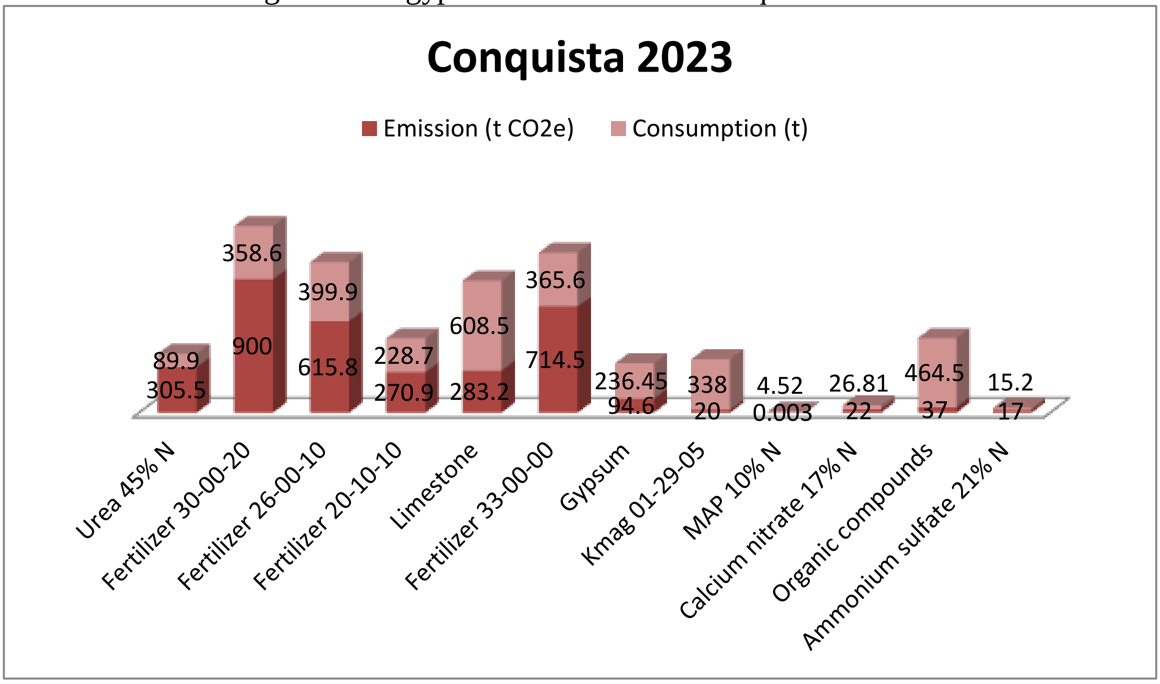


Figure 9 - Emissions from synthetic and organic nitrogen fertilizers, limestone and agricultural gypsum in 2023 at the Capoeirinha Unit

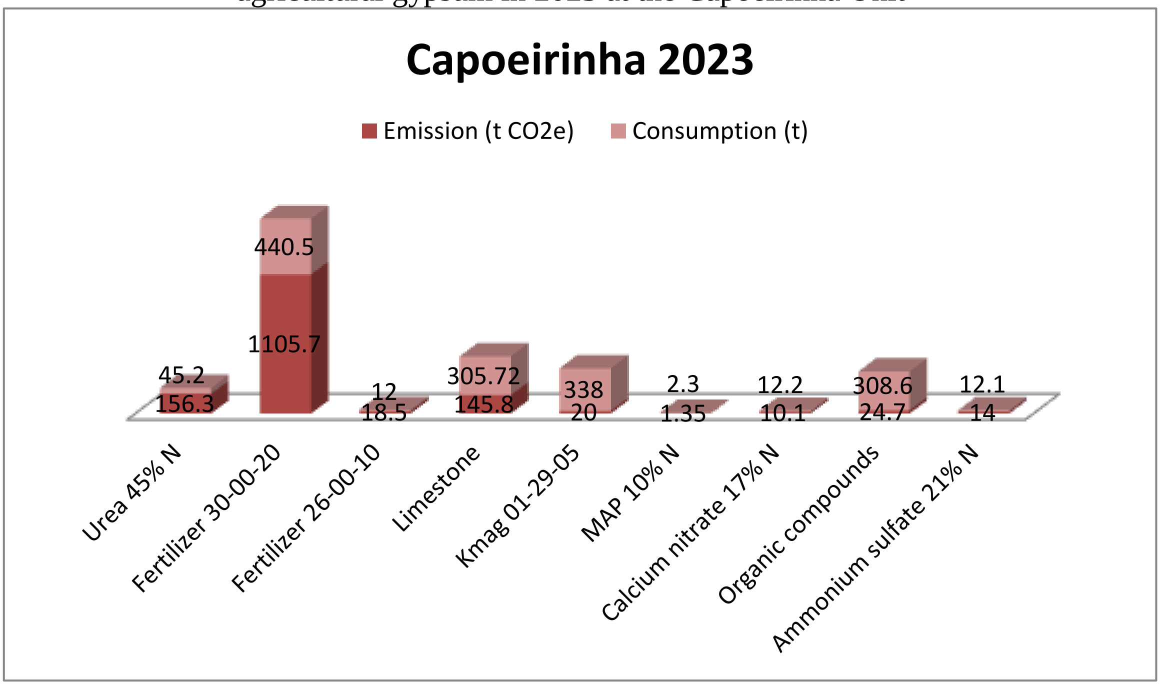


Figure 10 - Emissions from synthetic and organic nitrogen fertilizers, limestone and agricultural gypsum in 2023 at the Rio Verde Unit

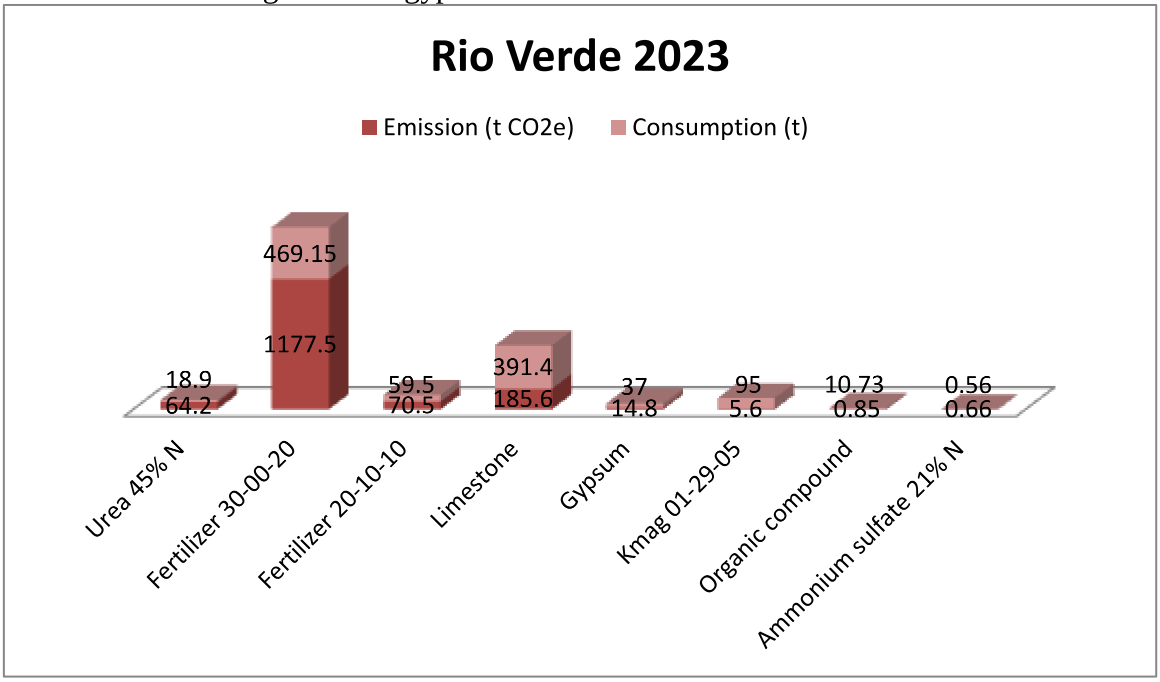
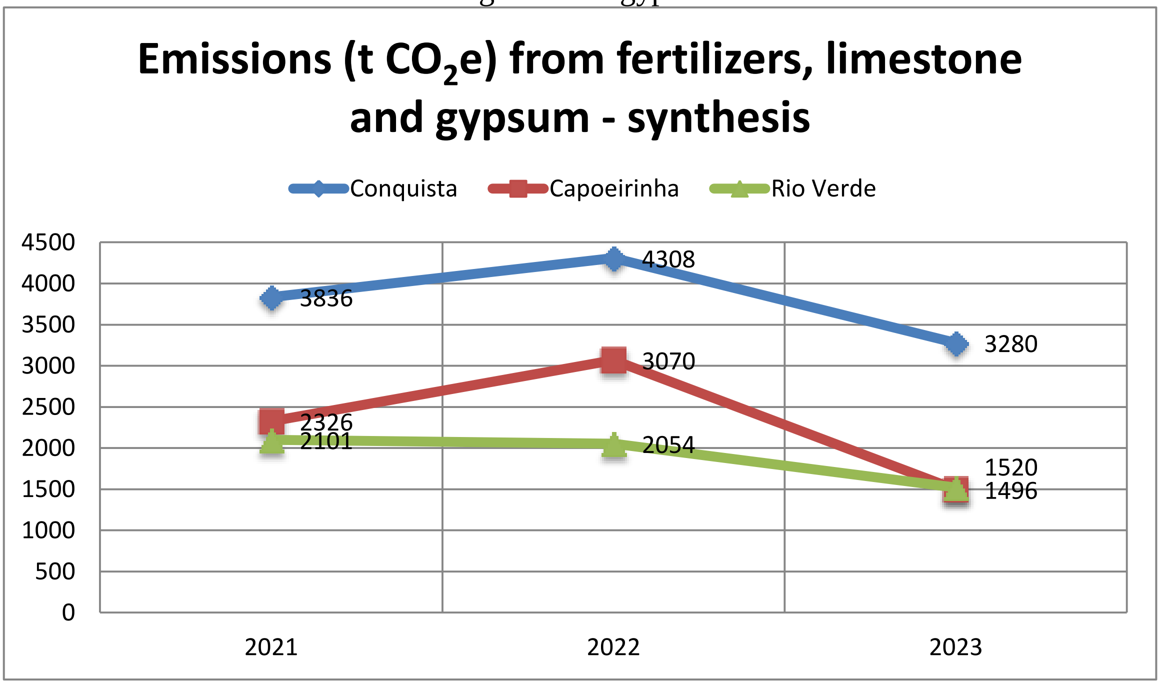


Figure 11 - Summary of emissions from synthetic and organic nitrogen fertilizers, limestone and agricultural gypsum in all units



2.2 SCOPE 1 - EMISSIONS FROM STATIONARY COMBUSTION (DIESEL, GASOLINE, FIREWOOD AND VEGETABLE WASTE) AND MOBILE COMBUSTION (DIESEL, GASOLINE AND LPG)

The Table 3 and Figure 12 show the emissions from stationary combustion at the Conquista unit.

Table 3 - Stationary combustion emissions in 2021, 2022 and 2023 at the Conquista unit

2021 - Conquista						
Fuel type	Consumption	Unit	Fossil fuel	Bio fuel	Fossil emissions ($t\ CO_2e$)	Bio emissions ($t\ CO_2$)
Diesel	52.678	L	Diesel	Biodiesel	123,93	14,45
Gasoline	117	L	Gasoline	Ethanol	0,19	0,05
Firewood	1588	t	-	Firewood	271,71	2885,62
2022 - Conquista						
Diesel	3916,5	L	Diesel	Biodiesel	9,21	1,07
Gasoline	109	L	Gasoline	Ethanol	0,18	0,05
Firewood	1313	t	-	Firewood	224,66	2385,9
Crop residues	168	t	-	Crop residues	18,44	195,07
2023 - Conquista						
Diesel	335	L	Diesel	Biodiesel	0,88	0,00067
Gasoline	842	L	Gasoline	Ethanol	2,95	1,75
Firewood	2273	t	-	Firewood	388,92	4130,36
Crop residues	590	t	-	Crop residues	64,74	685,08

Figure 12 - Stationary combustion emissions in 2021, 2022 and 2023 at the Conquista unit

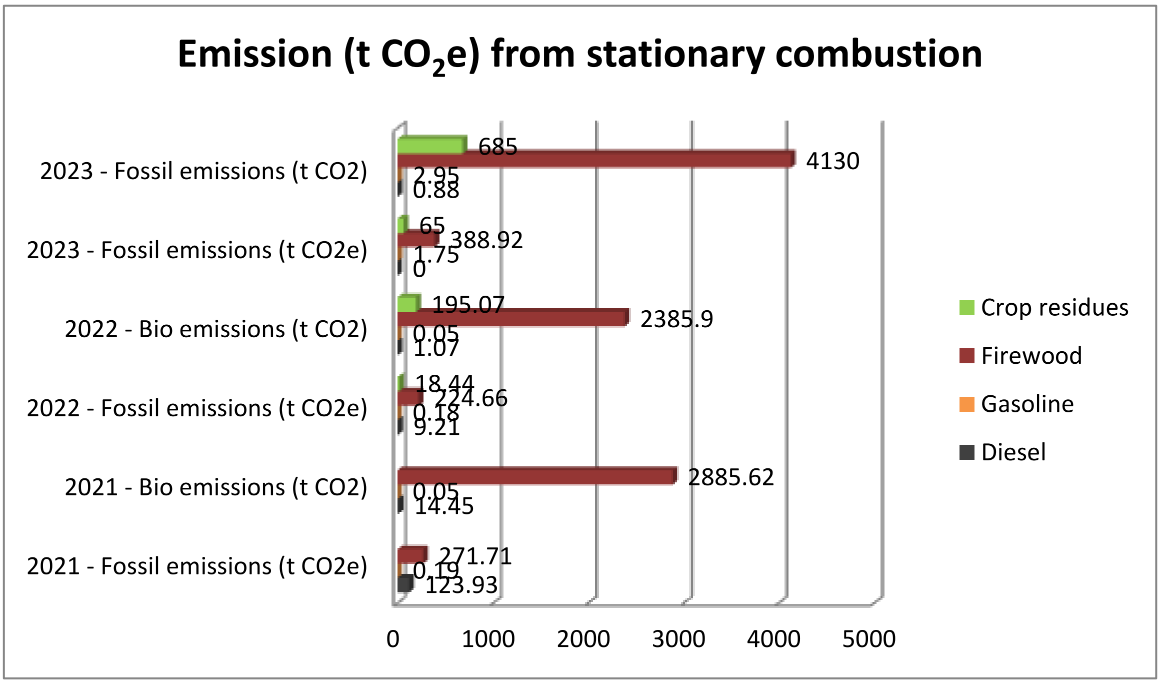
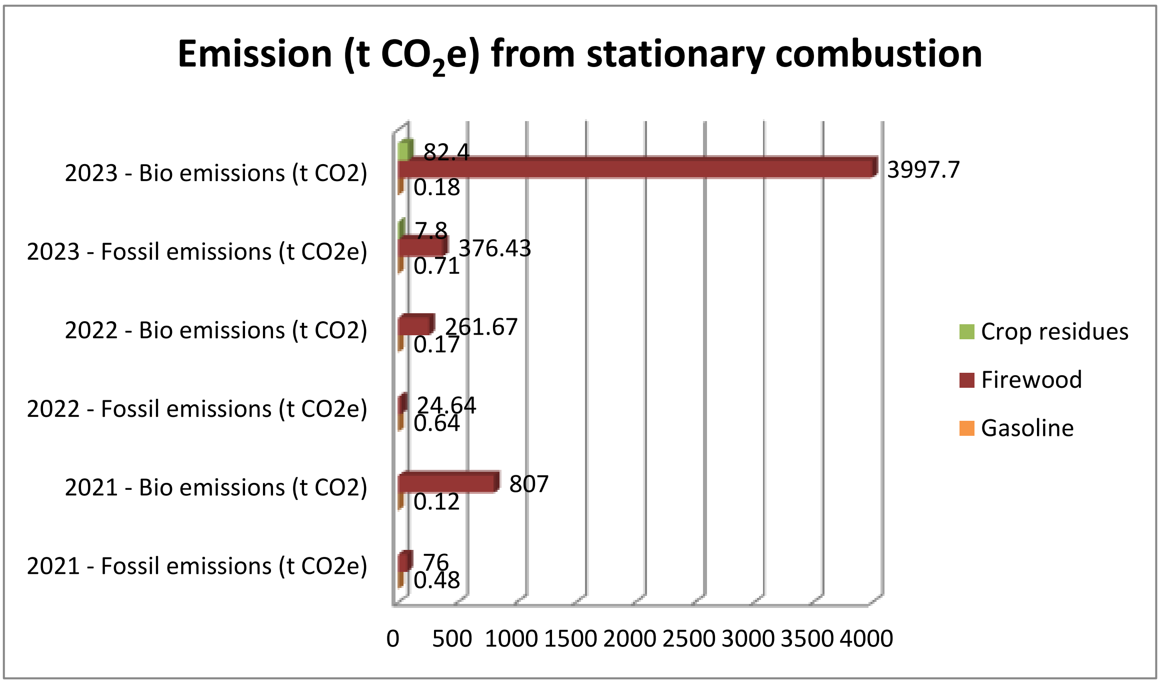


Table 4 and Figure 13 show the emissions from stationary combustion at the Capoeirinha unit.

Table 4 - Stationary combustion emissions in 2021, 2022 and 2023 at the Capoeirinha unit

2021 - Capoeirinha						
Fuel type	Consumption	Unit	Fossil fuel	Bio fuel	Fossil emissions ($t\ CO_2e$)	Bio emissions ($t\ CO_2$)
Gasoline	289	L	Gasoline	Ethanol	0.48	0.12
Firewood	444	t	-	Firewood	76	806.9
2022 – Capoeirinha						
Gasoline	388	L	Gasoline	Ethanol	0.64	0.17
Firewood	144	t	-	Firewood	24.64	261.67
2023 – Capoeirinha						
Gasoline	432	L	Gasoline	Ethanol	0.71	0.18
Firewood	2200	t	-	Firewood	376.43	3997.70
Crop residues	71	t	-	Crop residues	7.79	82.44

Figure 13 - Stationary combustion emissions in 2021, 2022 and 2023 at the Capoeirinha unit



The Table 5 and Figure 14 show the emissions from stationary combustion at the Rio Verde unit.

Table 5 - Emissions from stationary combustion in 2021, 2022 and 2023 at the Rio Verde unit

2021 - Rio Verde						
Fuel type	Consumption	Unit	Fossil fuel	Bio fuel	Fossil emissions ($t\ CO_2e$)	Bio emissions ($t\ CO_2$)
Gasoline	122	L	Gasoline	Gasoline	0.2	0.05
Firewood	454	t	-	Firewood	77.68	825
2022 - Rio Verde						
Gasoline	247	L	Gasoline	Gasoline	0.41	0.11
Firewood	488	t	-	Firewood	83.5	886.76
2023 - Rio Verde						

Gasoline	732	L	Gasoline	Gasoline	1.21	0.31
Firewood	605	t	-	Firewood	103.52	1099.37
Crop residues	71	t	-	Crop residues	7.8	82.44

Figure 14 - Stationary combustion emissions in 2021, 2022 and 2023 at the Rio Verde unit

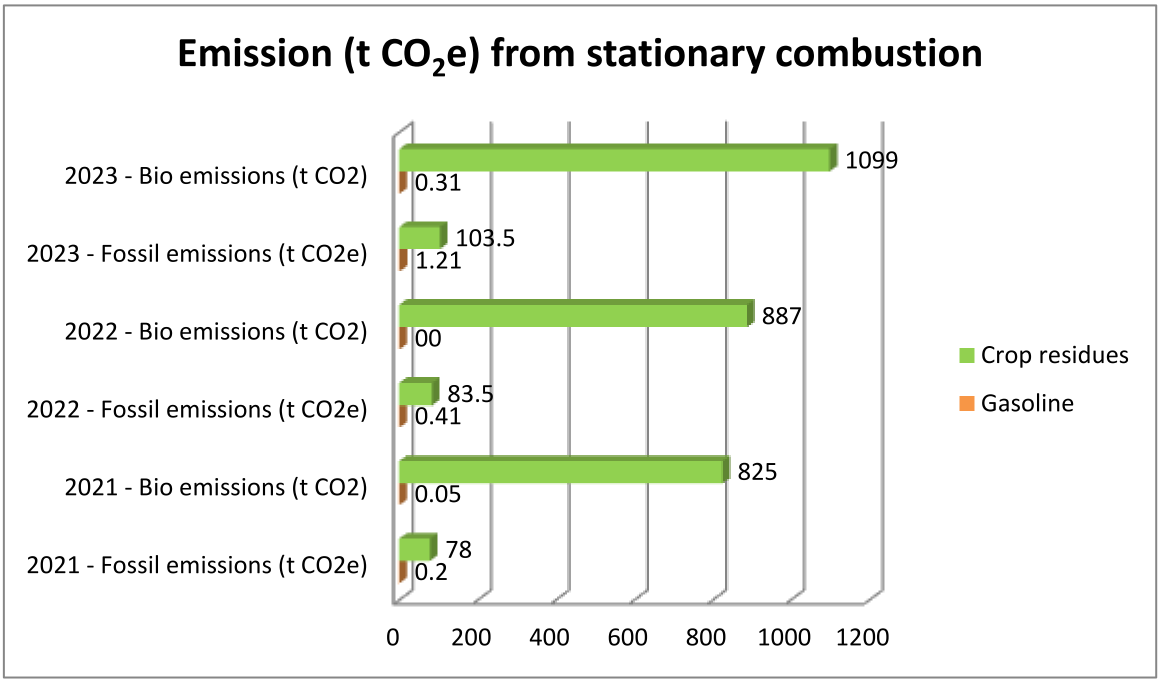


Figure 15 - Summary of emissions from stationary combustion in all units

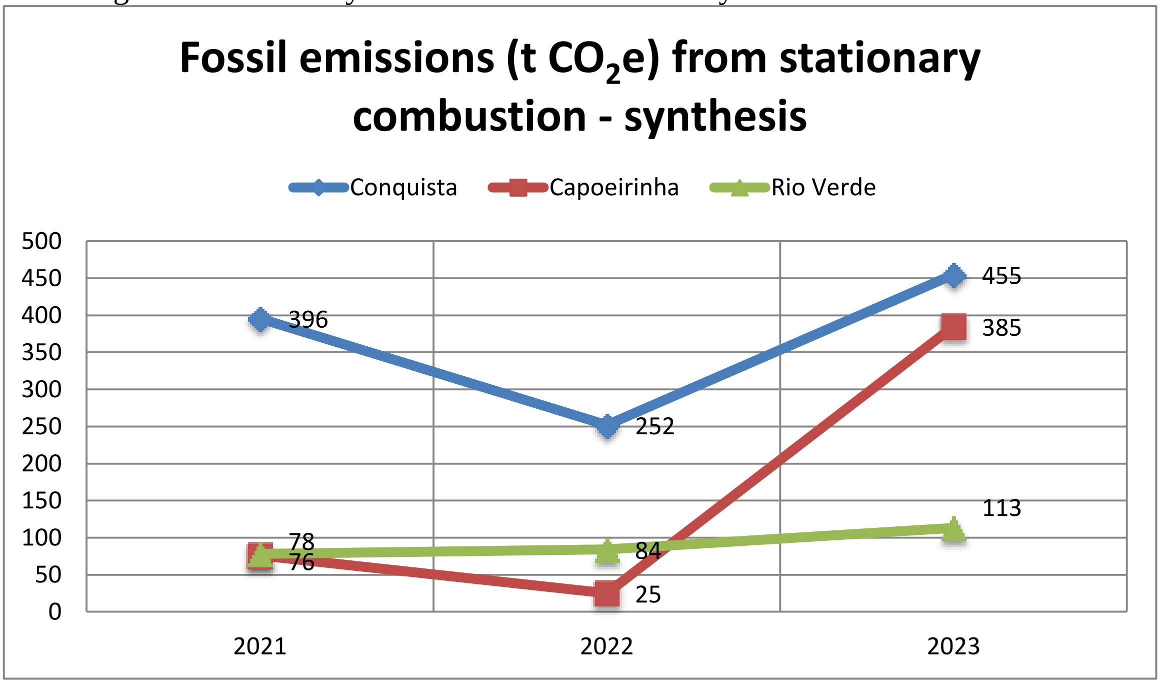


Figure 16 - Summary of biogenic emissions from stationary combustion in all units

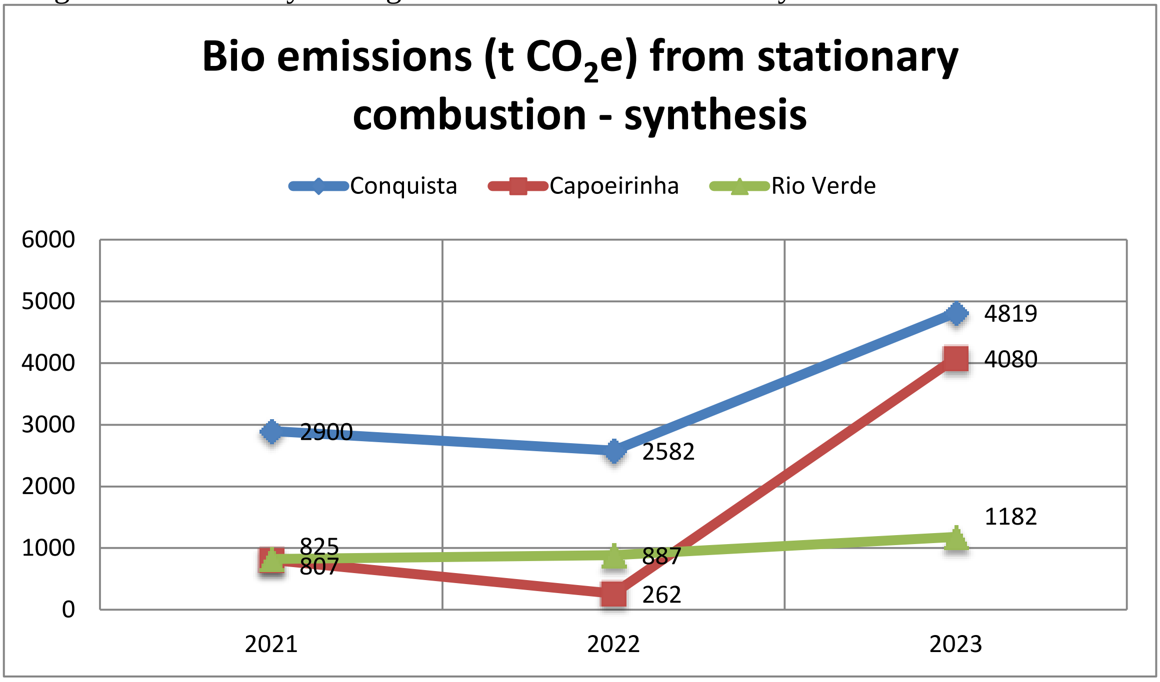


Table 6 and Figure 17 show the emissions from mobile combustion at the Conquista unit.

Table 6 - Emissions from mobile combustion in 2021, 2022 and 2023 at the Conquista unit

2021 - Conquista						
Fuel type	Consumption	Unit	Fossil fuel	Bio fuel	Fossil emissions (t CO_2e)	Bio emissions (t CO_2)
Diesel	504,523	L	Diesel	Biodiesel	1185.64	136.96
Gasoline	69,447	L	Gasoline	Ethanol	116.94	28.61
LPG	10,377	kg	LPG		31.30	
2022 – Conquista						
Diesel	362,858	L	Diesel	Biodiesel	852.72	98.50
Gasoline	52,075	L	Gasoline	Ethanol	87.70	21.46
LPG	20,183	kg	LPG		60.86	
2023 – Conquista						
Diesel	433,409	L	Diesel	Biodiesel	1018.52	117.65
Gasoline	3372	L	Gasoline	Ethanol	5.70	1.40
LPG	21,866	kg	LPG		65.94	

Figure 17 - Emissions from mobile combustion in 2021, 2022 and 2023 at the Conquista unit

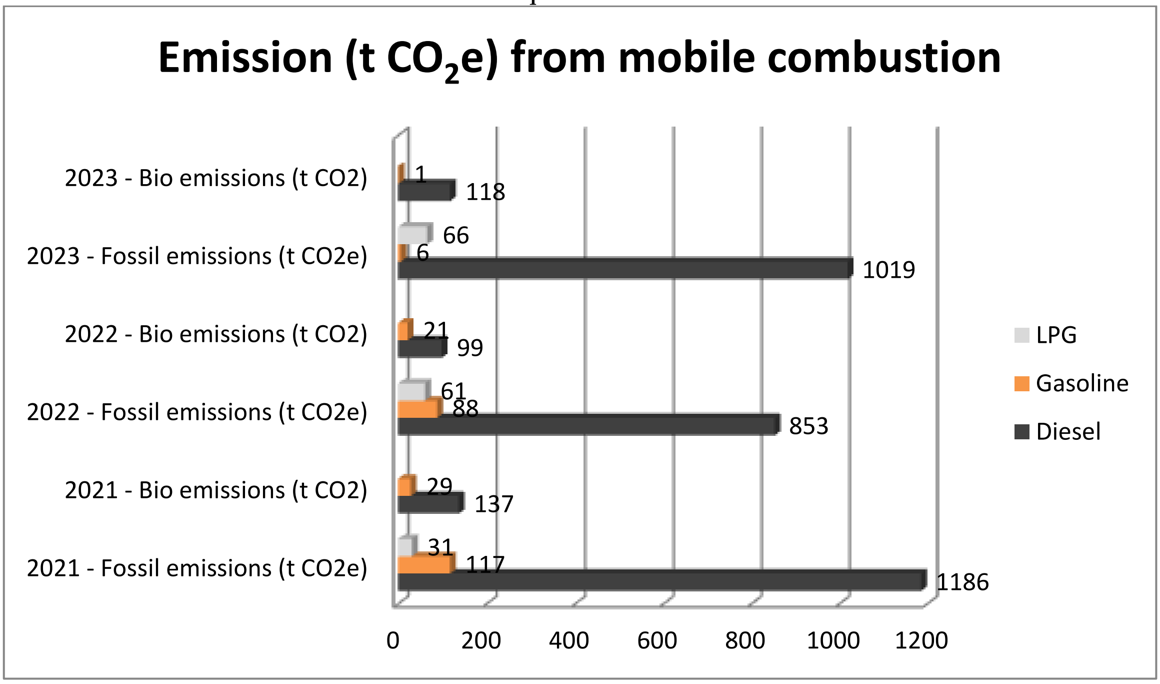


Table 7 and Figure 18 show the emissions from mobile combustion at the Capoeirinha unit.

Table 7 - Emissions from mobile combustion in 2021, 2022 and 2023 at the Capoeirinha unit

2021 - Capoeirinha						
Fuel type	Consumption	Unit	Fossil fuel	Bio fuel	Fossil emissions ($t\ CO_2e$)	Bio emissions ($t\ CO_2$)
Diesel	311,400	L	Diesel	Biodiesel	731.80	84.53
Gasoline	7874	L	Gasoline	Ethanol	13.26	3.24
2022 – Capoeirinha						
Diesel	266,469	L	Diesel	Biodiesel	619.16	71.52
Gasoline	10,530	L	Gasoline	Ethanol	17.72	4.34
2023 - Capoeirinha						
Diesel	308,615	L	Diesel	Biodiesel	725.25	83.78
Gasoline	10,135	L	Gasoline	Ethanol	17.07	4.20

Figure 18 - Emissions from mobile combustion in 2021, 2022 and 2023 at the Capoeirinha unit

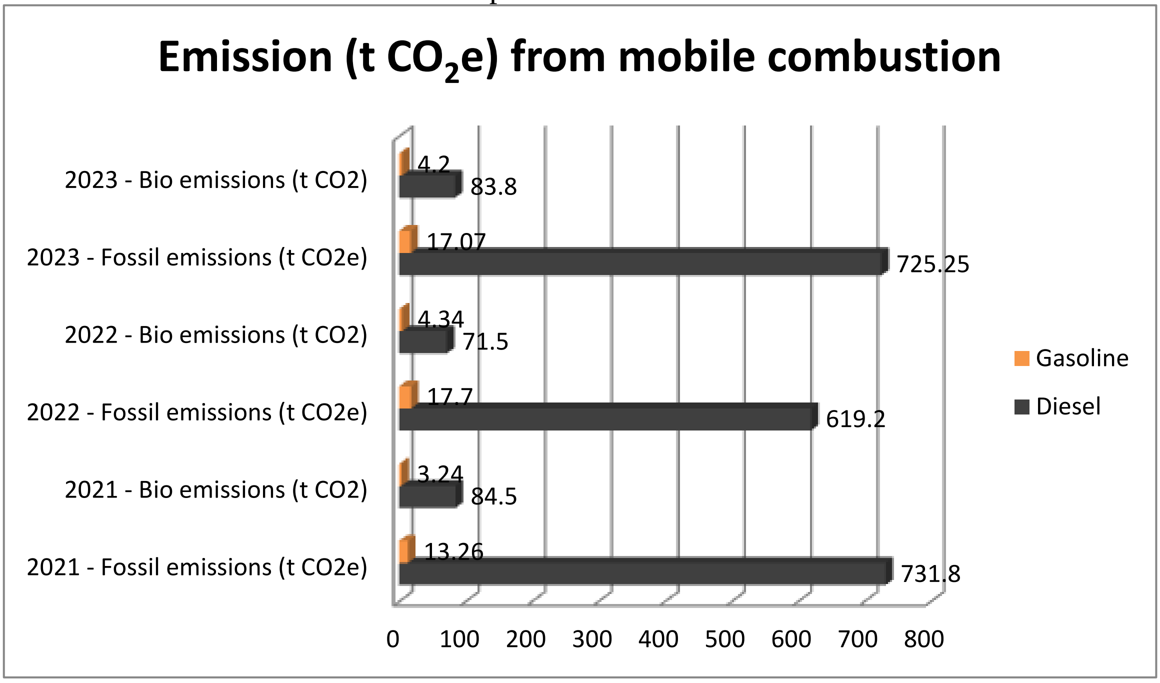
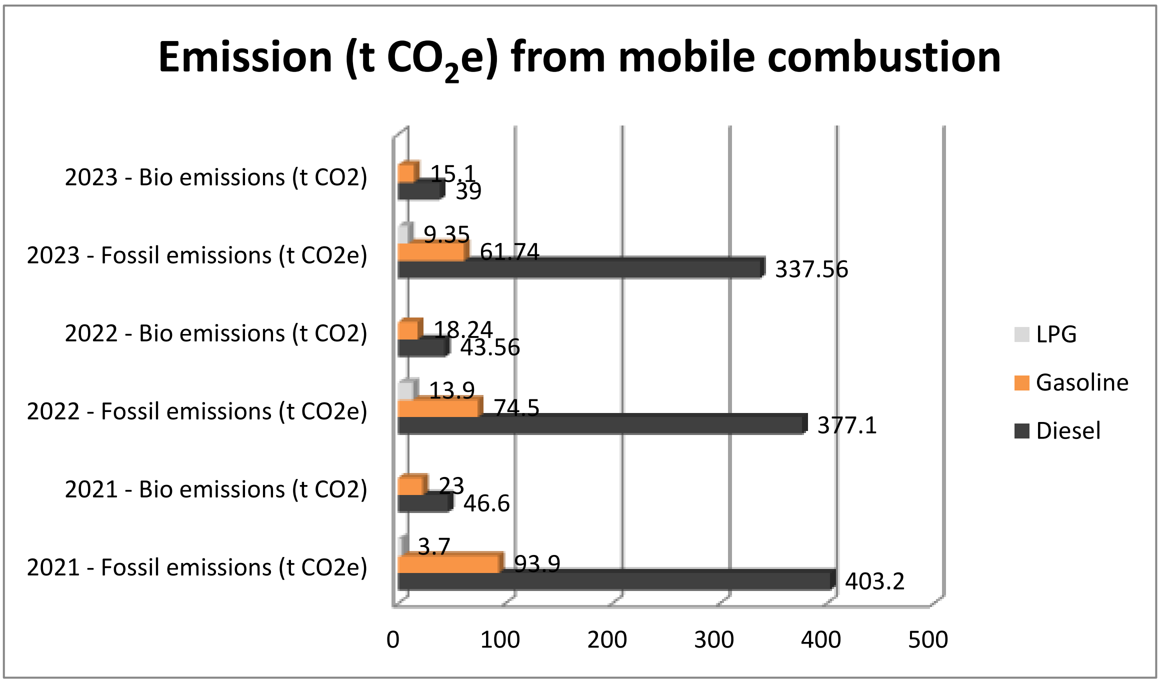


Table 8 and Figure 19 show the emissions from mobile combustion at the Rio Verde unit.

Table 8 - Emissions from mobile combustion in 2021, 2022 and 2023 at the Rio Verde unit

2021 - Rio Verde						
Fuel type	Consumption	Unit	Fossil fuel	Bio fuel	Fossil emissions ($t\ CO_2e$)	Bio emissions ($t\ CO_2$)
Diesel	171,575	L	Diesel	Biodiesel	403.20	46.58
Gasoline	55,762	L	Gasoline	Ethanol	93.90	23
LPG	1230	kg	LPG		3.71	
2022 - Rio Verde						
Diesel	160,458	L	Diesel	Biodiesel	377.10	43,56
Gasoline	44,278	L	Gasoline	Ethanol	74,52	18.24
LPG	4600	kg	LPG		13.87	
2023 - Rio Verde						
Diesel	143,640	L	Diesel	Biodiesel	337.56	39
Gasoline	36,667	L	Gasoline	Ethanol	61.74	15.11
LPG	3102	kg	LPG		9.35	

Figure 19 - Emissions from mobile combustion in 2021, 2022 and 2023 at the Rio Verde unit



The figures 20 and 21 summarize fossil and biogenic emissions from mobile combustion in all units.

Figure 20 - Summary of emissions from mobile combustion in all units

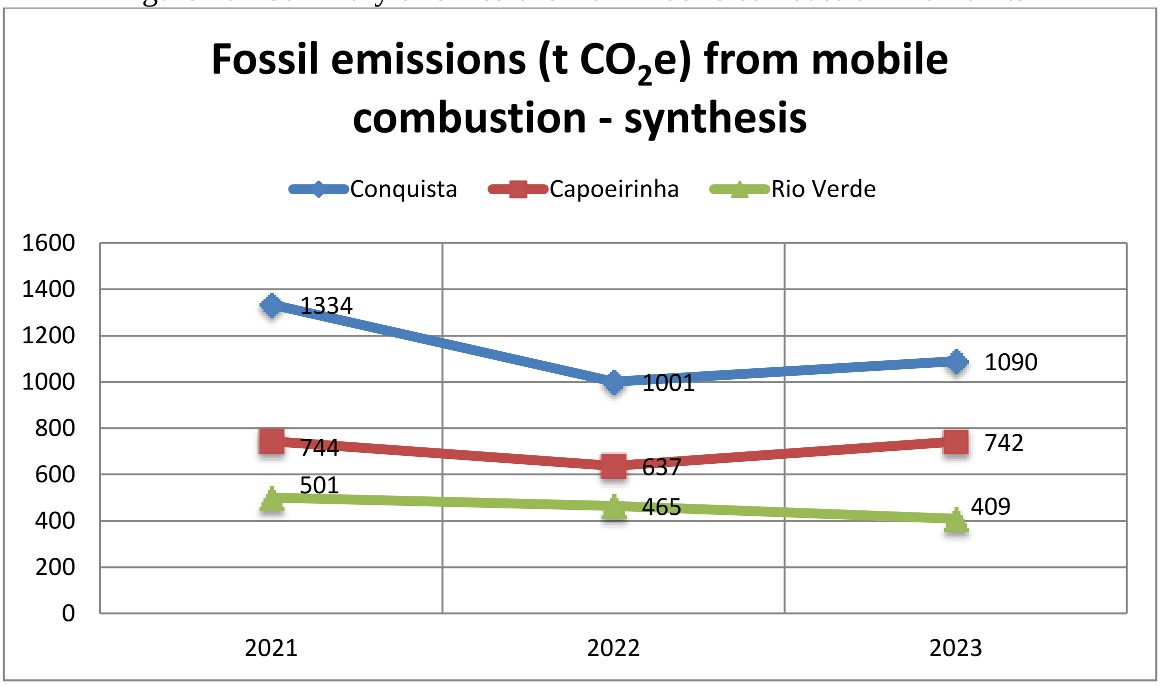
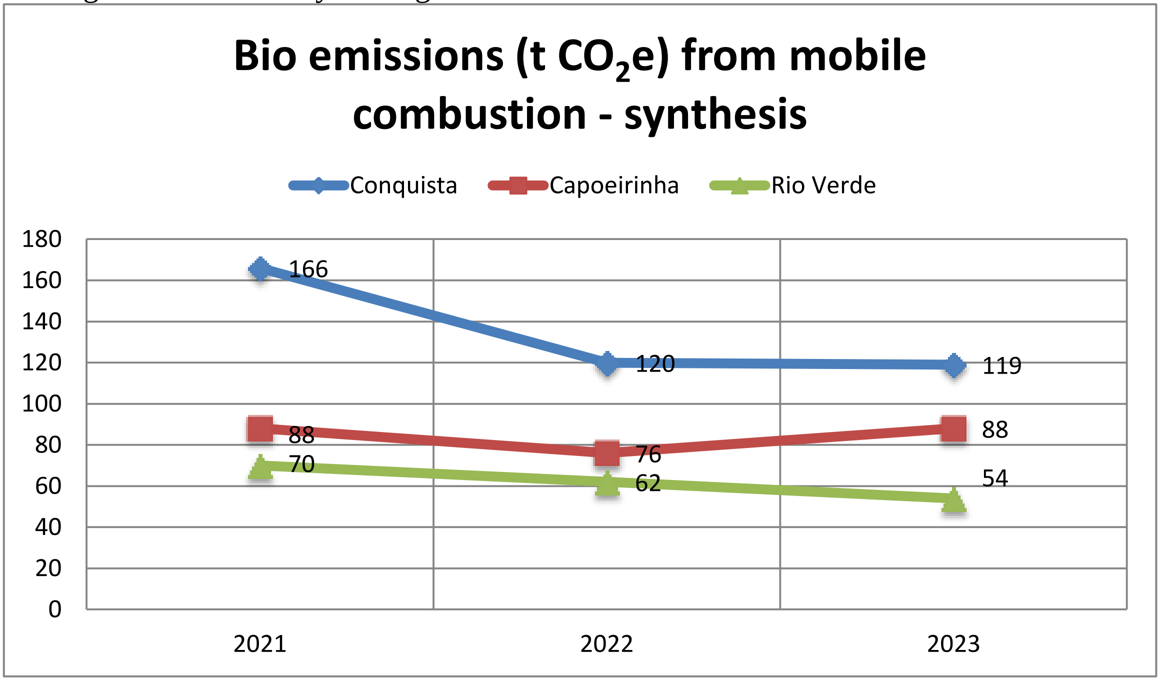


Figure 21 - Summary of biogenic emissions from mobile combustion in all units



2.3 EMISSIONS FROM LIQUID EFFLUENT TREATMENT:

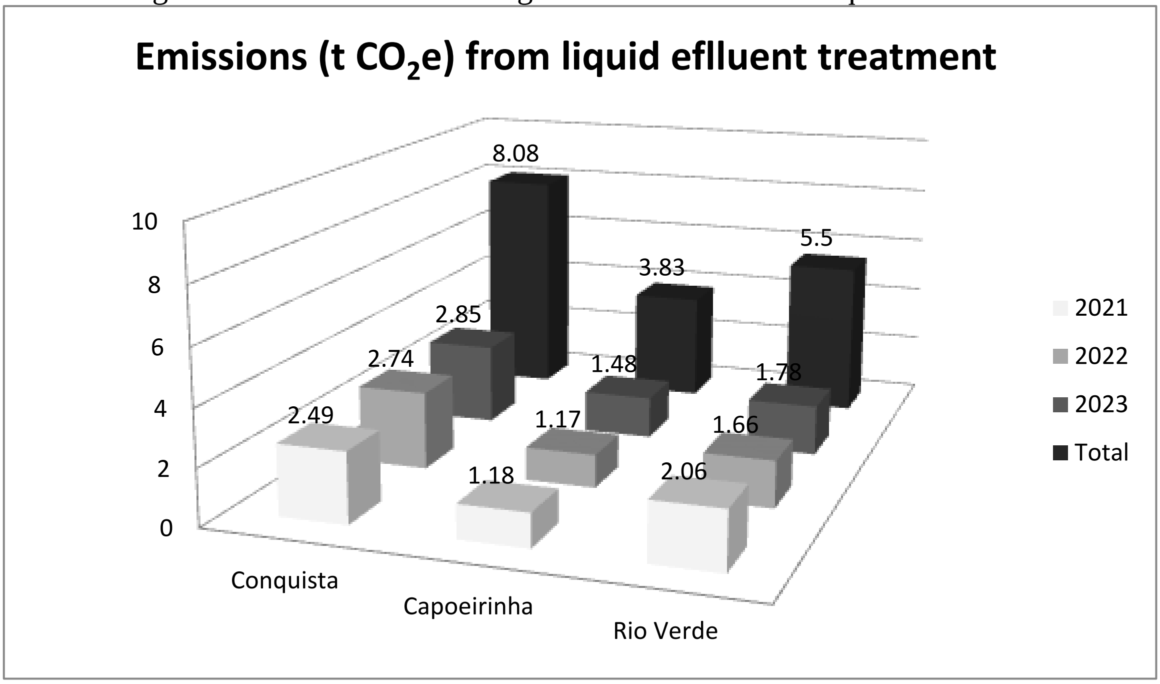
The emissions are shown in Table 9 and Figure 22:

Table 9 – Emissions resulting from the treatment of liquid effluents

Unit	Year	*N	BOD (g/pe/day)	DW	B_O	MCF	Emissions (t CO_2e)
Conquista	2021	430	50	13.79	0.6	0.5	2.49
	2022	440		14.75			2.74
	2023	450		15.06			2.85
	Total	-		-			8.08
Capoeirinha	2021	163	50	17.27	0.6	0.5	1.18
	2022	187		14.85			1.17
	2023	227		15.52			1.48
	Total	-		-			3.83
Rio Verde	2021	277	50	17.41	0.6	0.5	2.06
	2022	259		14.94			1.66
	2023	275		15.46			1.78
	Total	-		-			5.50

*employees number

Figure 22 – Emissions resulting from the treatment of liquid effluents



2.4 CO_2 REMOVALS:

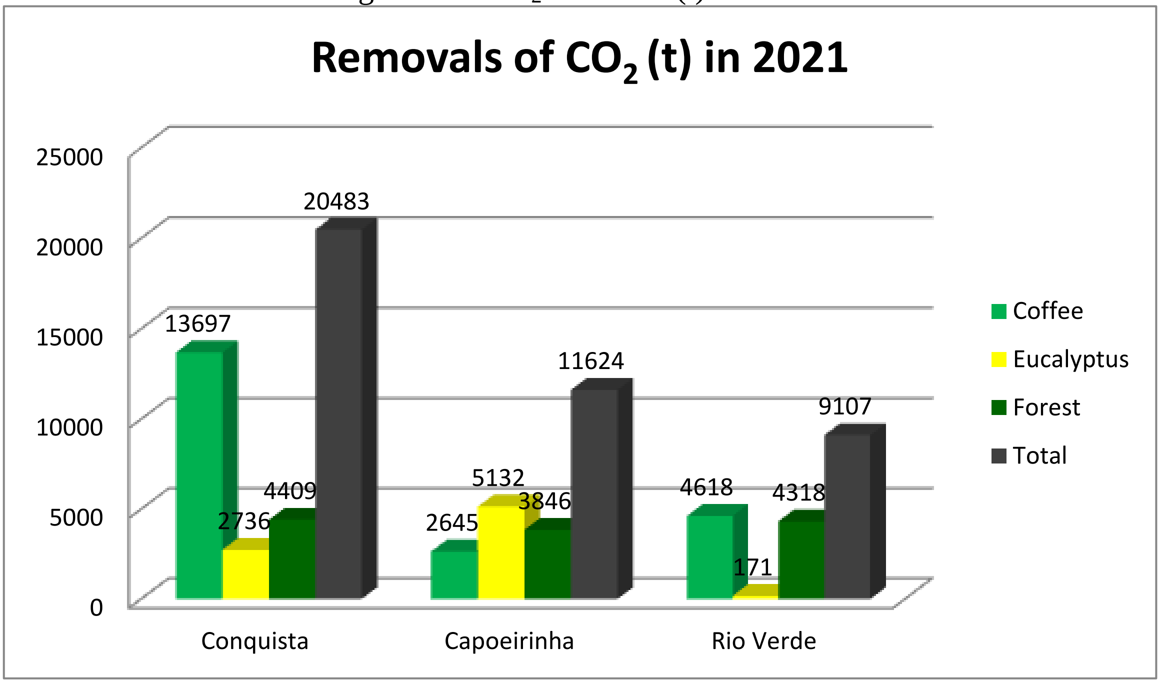
The 2021 results are shown in Table 10 and Figure 23.

Table 10 - CO_2 removals (t) in 2021

Unit	Class	*Long. (yrs)	A (ha)	Plants (ha)	$Tc_{biomass}$ (m³/plant/yr)	d (g/cm³)	$C_{\%}$	Removal (t CO_2)
Conquista	Coffee	15	1024.95	4453	0.005	0.62	0.44	13,697.2
	Eucalyptus	21	71.82	1852	0.025	0.51	0.47	2736.3
	Forest	40	178.51	952	0.024	0.67	0.47	4409.1
	Total							20,482.57
Capoeirinha	Coffee	15	201.71	4370	0.005	0.62	0.44	2645.36
	Eucalyptus	21	152.40	1637	0.025	0.51	0.47	5132.24
	Forest	40	129.35	1146	0.024	0.67	0.47	3845.92
	Total							11,623.53
Rio Verde	Coffee	15	346.76	4438	0.005	0.62	0.44	4618.41
	Eucalyptus	21	4.50	1852	0.025	0.51	0.47	171.44
	Forest	40	182.27	913	0.024	0.67	0.47	4317.53
	Total							9107.39

*longevity

Figure 23 – CO_2 removals (t) in 2021

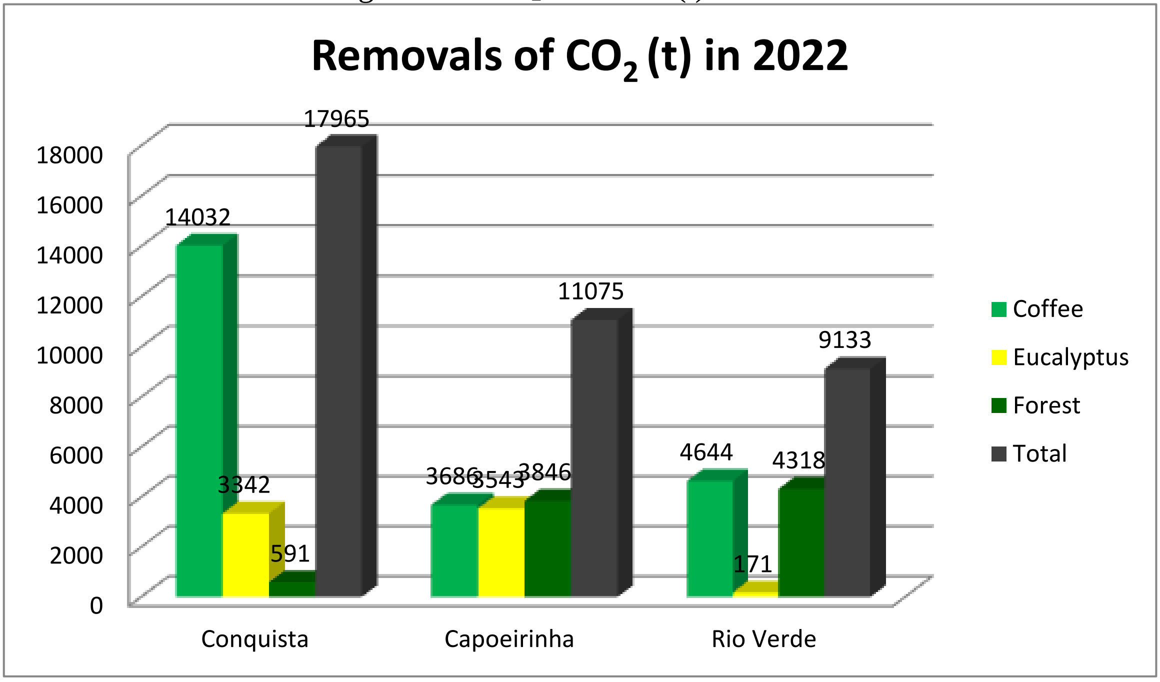


The 2022 results are shown in Table 11 and Figure 24.

Table 11 – CO_2 removals (t) in 2022

Unit	Class	*Long. (yrs)	A (ha)	Plants (ha)	$Tc_{biomass}$ (m^3/plant/yr)	d (g/cm³)	$C_{\%}$	Removal (t CO_2)
Conquista	Coffee	15	1089.61	4291.17	0.005	0.62	0.44	14,032.12
	Eucalyptus	21	86.02	1888.46	0.025	0.51	0.47	3341.80
	Forest	40	23.72	961	0.024	0.67	0.47	591.40
	Total							17,965.33
Capoeirinha	Coffee	15	303.02	4053.66	0.005	0.62	0.44	3686.33
	Eucalyptus	21	105.81	1627.54	0.025	0.51	0.47	3542.70
	Forest	40	129.35	1146	0.024	0.67	0.47	3845.92
	Total							11,074.94
Rio Verde	Coffee	15	354.46	4366	0.005	0.62	0.44	4644.37
	Eucalyptus	21	4.50	1852	0.025	0.51	0.47	171.44
	Forest	40	182.27	913	0.024	0.67	0.47	4317.53
	Total							9133.35

Figure 24 – CO_2 removals (t) in 2022

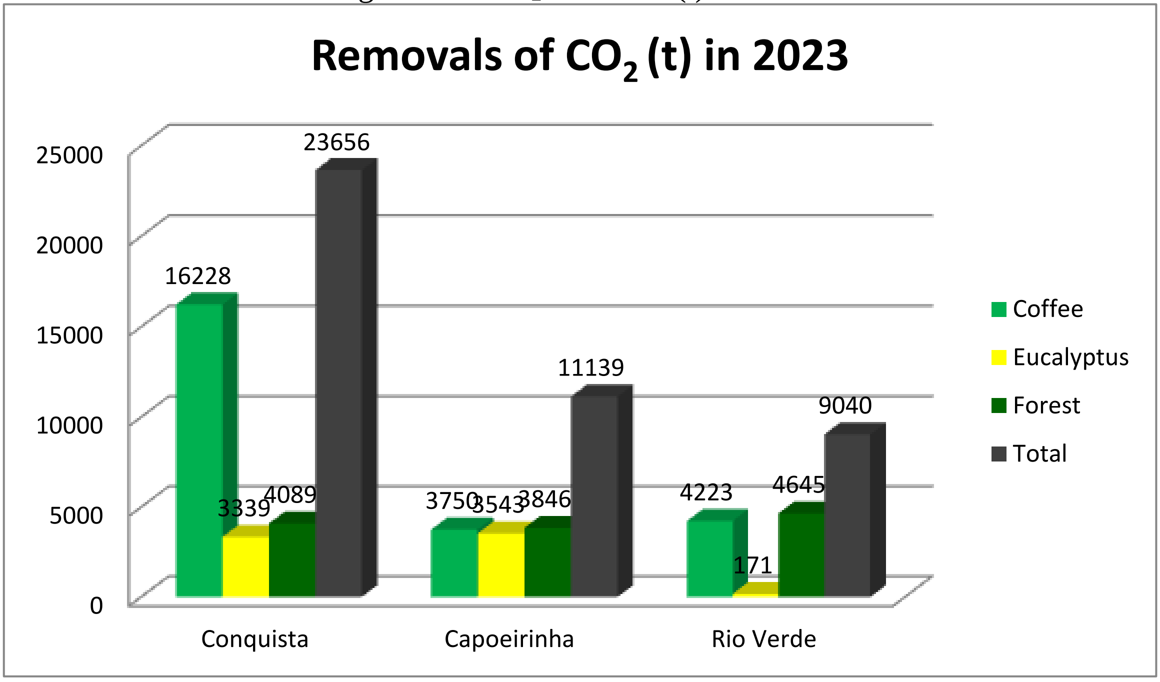


The 2023 results are shown in Table 12 and Figure 25.

Table 11 – CO_2 removals (t) in 2023

Unit	Class	*Long. (yrs)	A (ha)	Plants (ha)	$Tc_{biomass}$ (m^3/plant/yr)	d (g/cm^3)	$C_{\%}$	Removal (t CO_2)
Conquista	Coffee	15	1246	4339.76	0.005	0.62	0.44	16,227.82
	Eucalyptus	21	85.96	1888.46	0.025	0.51	0.47	3339.47
	Forest	40	164	961	0.024	0.67	0.47	4089
	Total							23,656.29
Capoeirinha	Coffee	15	301.72	4141.15	0.005	0.62	0.44	3749.74
	Eucalyptus	21	105.81	1627.54	0.025	0.51	0.47	3542.70
	Forest	40	129.35	1146	0.024	0.67	0.47	3845.92
	Total							11,138.35
Rio Verde	Coffee	15	314.18	4479	0.005	0.62	0.44	4223.14
	Eucalyptus	21	4.50	1852	0.025	0.51	0.47	171.44
	Forest	40	212.91	840.91	0.024	0.67	0.47	4645.10
	Total							9039.70

Figure 25 – CO_2 removals (t) in 2023



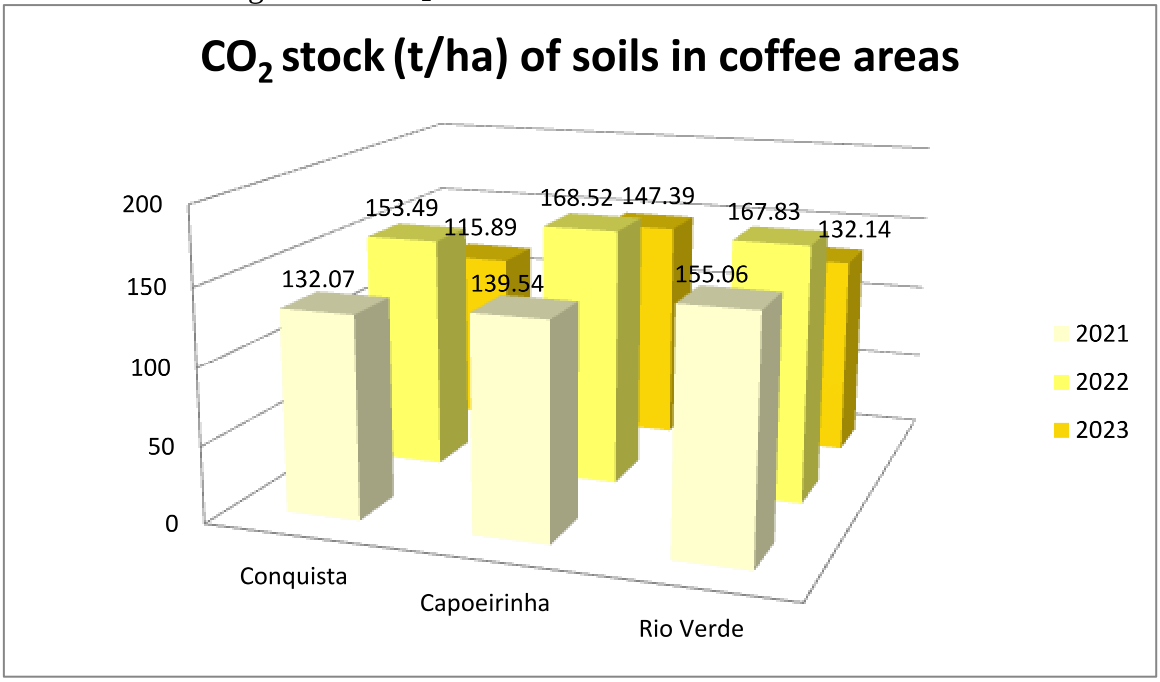
2.5 SOIL C STOCKS UNDER COFFEE CULTIVATION:

The results for all years are shown in Table 12 and Figure 26.

Table 12 – Soil C and CO_2 stocks under coffee cultivation

Unit	Year	C stock 0-20 cm (t)	CO_2 stock ($ST.CO_2$) 0-20 cm (t)	Ha (util area)	CO_2 stock / ha (t)
Conquista	2021	48,168.33	172,296	1304.51	132.07
	2022	54,708	200,231	1304.51	153.49
	2023	41,307.15	151,185	1304.51	115.89
Capoeirinha	2021	27,234.81	99,679	714.32	139.54
	2022	33,074.44	121,052	718.32	168.52
	2023	28,928.75	105,879	718.32	147.39
Rio Verde	2021	25,759.32	94,279	608	155.06
	2022	27,880.90	102,045	608	167.83
	2023	21,947.38	80,347	608	132.14

Figure 26 – CO_2 stock in soils under coffee cultivation



2.6 SCOPE 2: CO_2 (t) EMISSIONS FROM ELECTRICITY CONSUMPTION

Emissions from electricity consumption are shown in Table 13 and Figures 27,28,29 and 30.

Table 13 – CO_2e emissions (t) from electricity consumption

Index	Year	Total Megawatt (MWh)	Emission factors (tCO_2 MWh^{-1})	Total emission (t CO_2e.)
	2021	4346.51	0.1264	549.40
Conquista	2022	2887.32	0.0426	125.14
	2023	3700.26	0.0385	142.46
TOTAL	-	10,934.09	-	817
	2021	558.30	0.1264	70.57
Capoeirinha	2022	445.30	0.0426	18.97
	2023	541.29	0.0385	20.84
TOTAL	-	1544.89	-	110.38
	2021	403.08	0.1264	50.95
Rio Verde	2022	343.90	0.0426	14.35
	2023	404.67	0.0385	15.58
TOTAL	-	1151.65	-	80.88

Figure 27 – Electricity emission by category in the Conquista unit

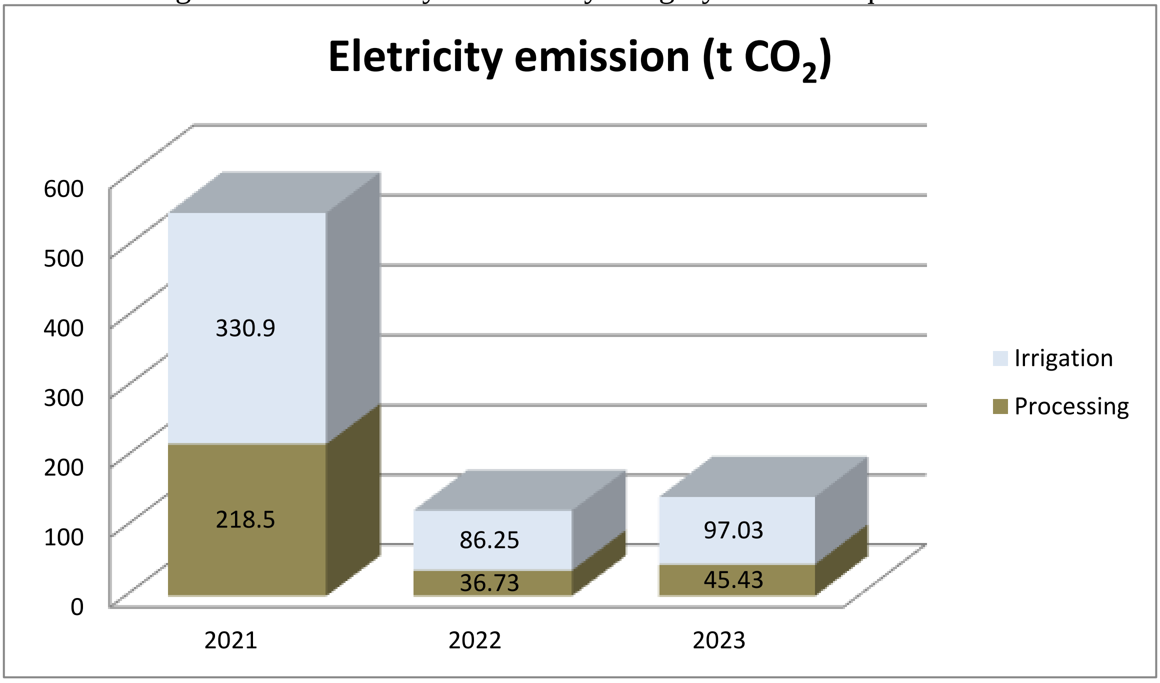


Figure 28 – Electricity emission by category in the Capoeirinha unit

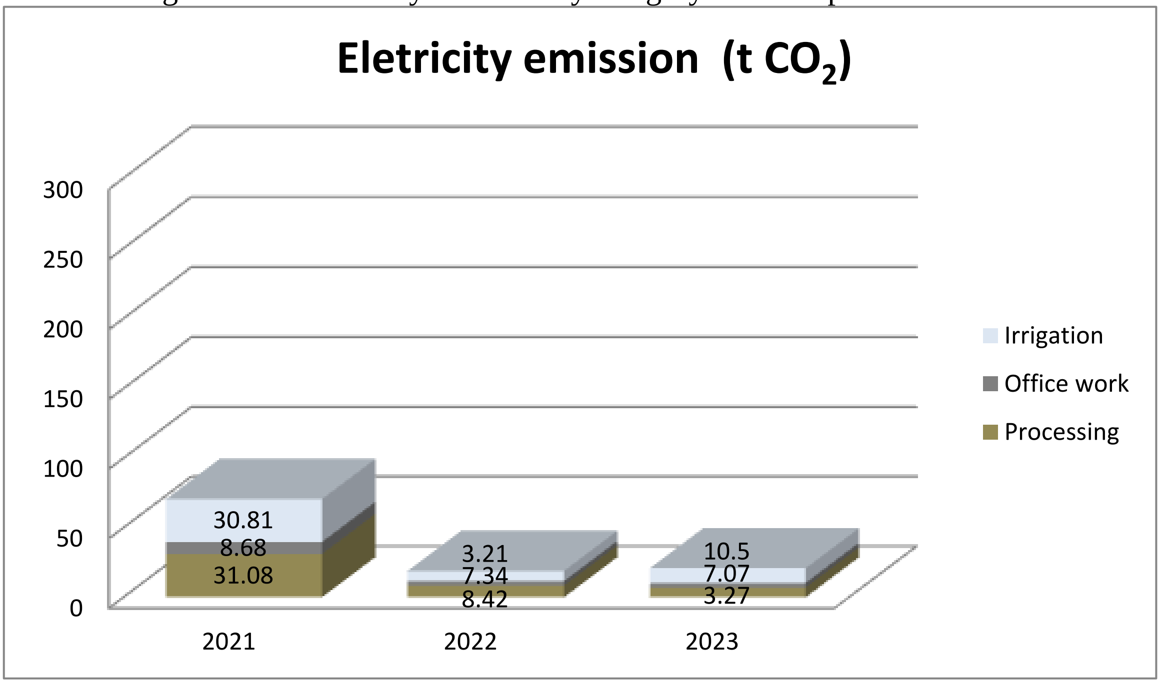


Figure 29 – Electricity emission by category at the Rio Verde unit

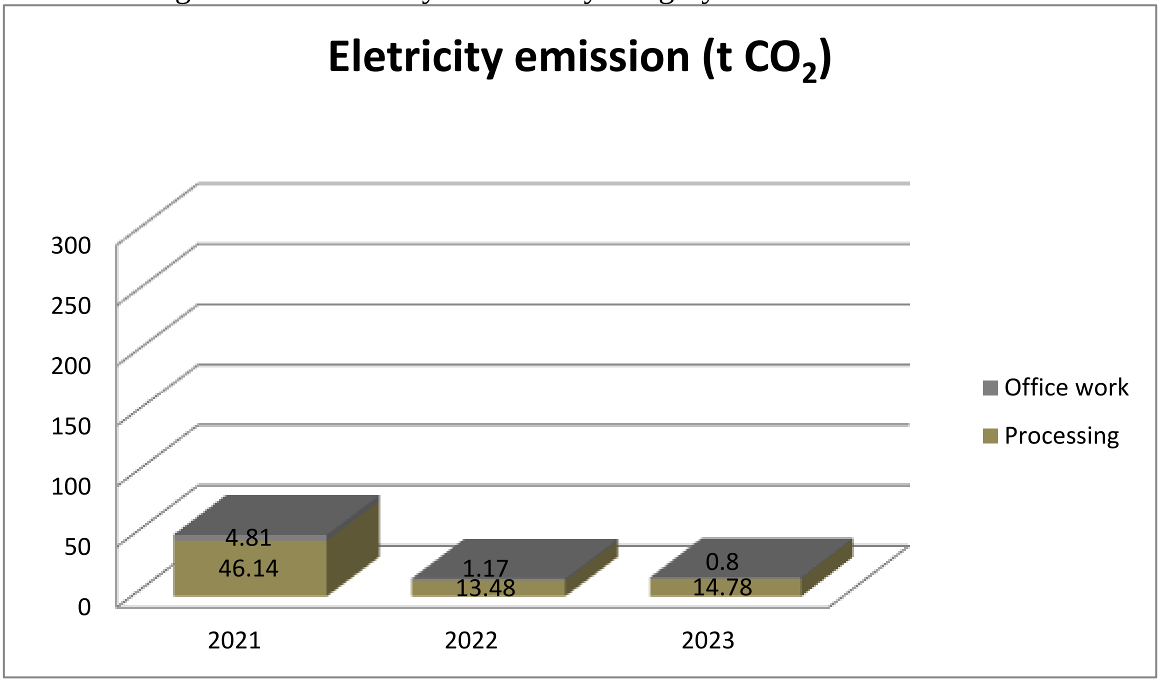
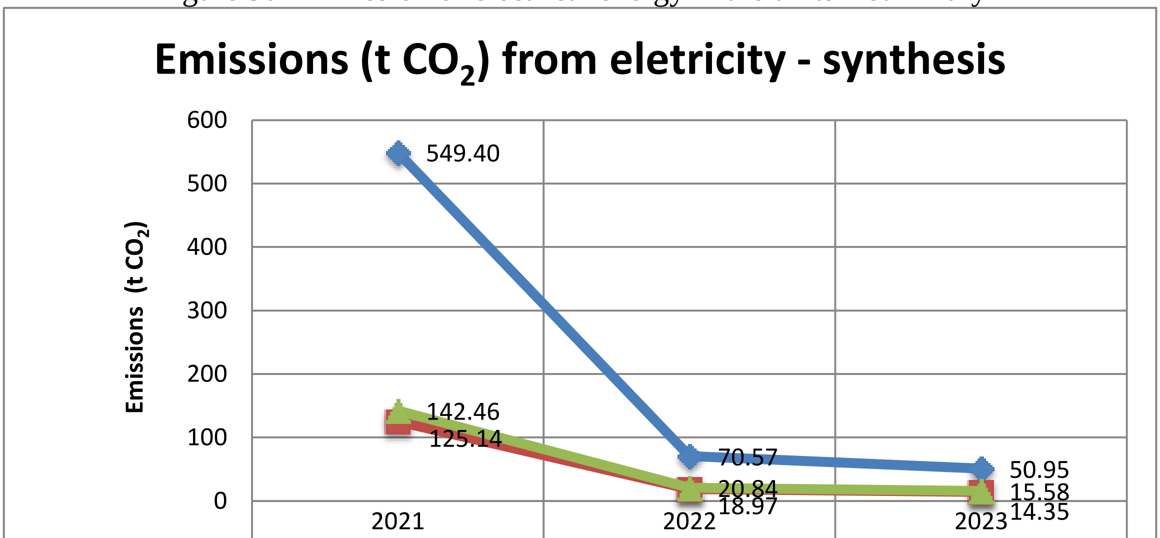


Figure 30 – Emission of electrical energy in the units – summary



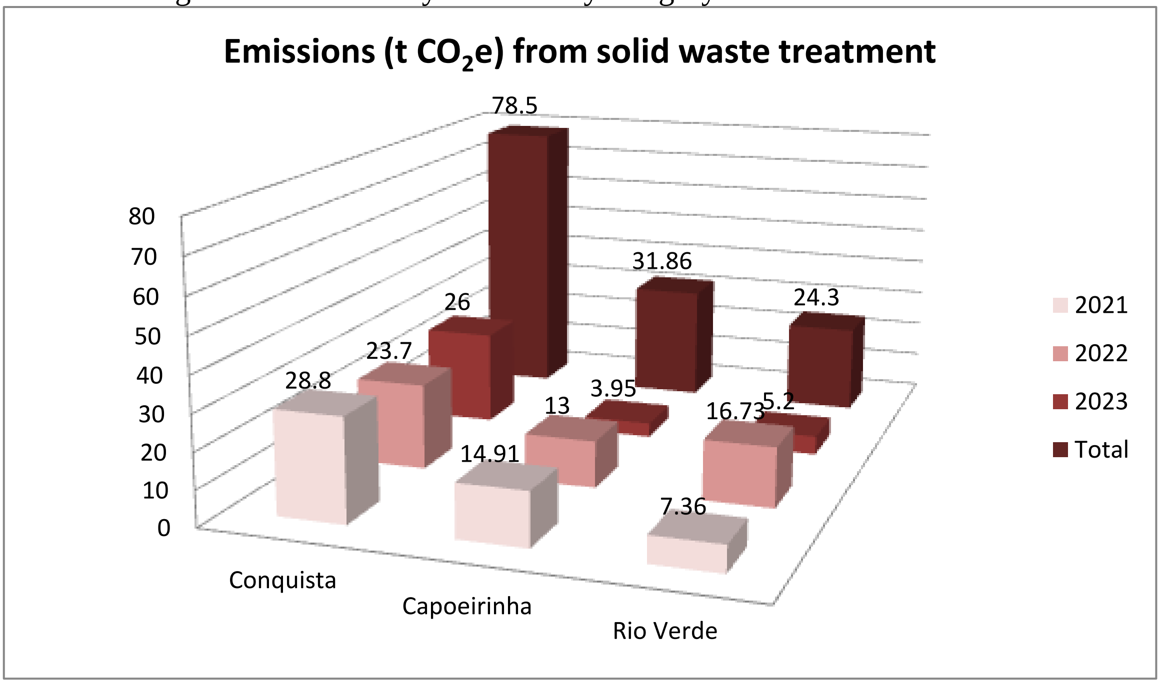
	2021	2022	2023
Conquista	549.4	70.57	50.95
Capoeirinha	125.14	18.97	14.35
Rio Verde	142.46	20.84	15.58

2.7 SCOPE 3 - CO_2e (t) EMISSIONS FROM THE TREATMENT OF SOLID WASTE GENERATED:

Table 14 – Emissions from solid waste treatment

Unit	Year	M_{WT} (kg)	DOC (kg C/kg res.)	DOC_f	DOC_T (kg)	CH_{4I} (kg)	F	O_X	CH_{4F} (kg)	Emissions t (CO_2e)
Conquista	2021	38,080	0.15	0.5	2856	3807	0.6	0.1	1027.90	28.80
	2022	31,310			2348	3129			846	23.70
	2023	34,230			2567	3422			924	25.99
	Total	103,620								78.49
Capoeirinha	2021	19,670	0.15	0.5	1475	1966	0.6	0.1	531	14.91
	2022	16,840			1263	1684			455	13.01
	2023	5200			390	520			140	3.95
	Total	41,350								31.87
Rio Verde	2021	10,054	0.15	0.5	754	1005	0.6	0.1	271	7.36
	2022	22,230			1667	2222			600	16.73
	2023	6910			518	690			186	5.20
	Total	39,194								24.29

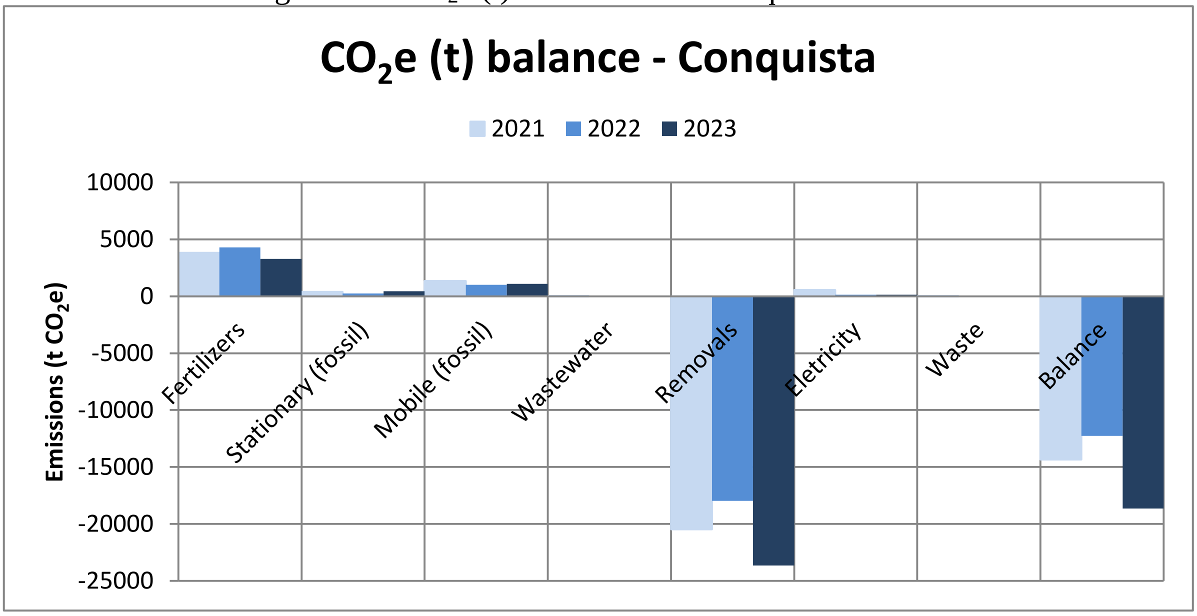
Figure 31 – Electricity emission by category at the Rio Verde unit



2.8 CO_2e BALANCE

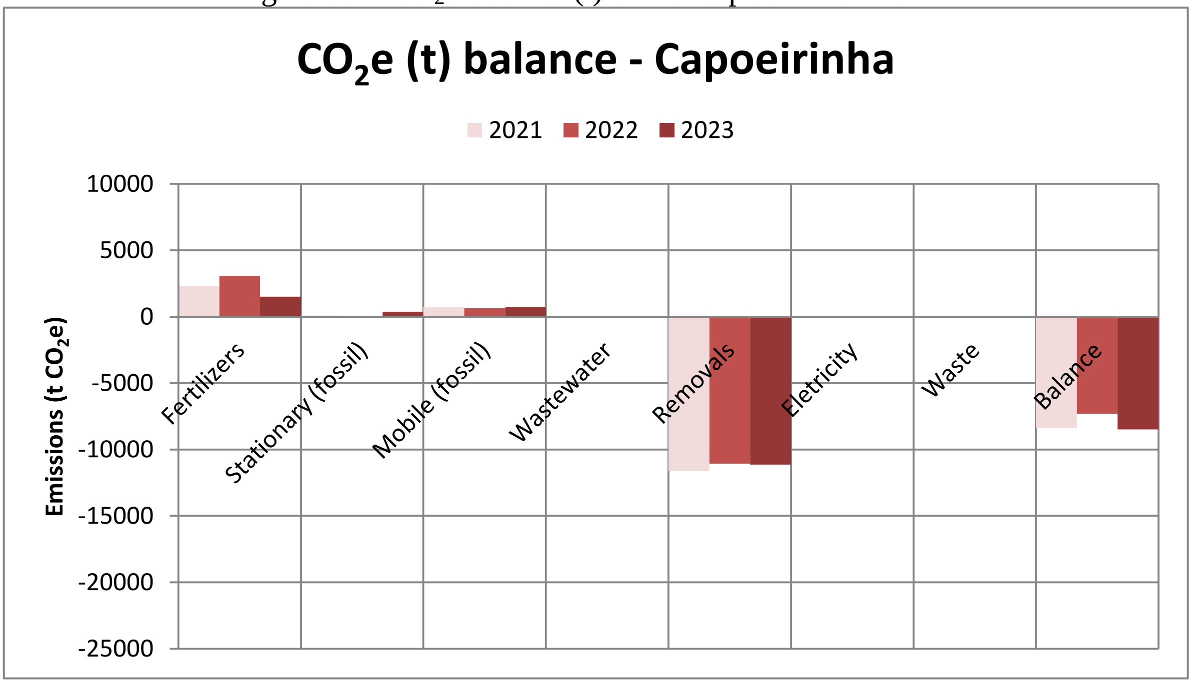
The CO_2e balance was categorized by unit; below is that of Conquista (Figure 32):

Figure 32 – CO_2e (t) balance of the Conquista unit



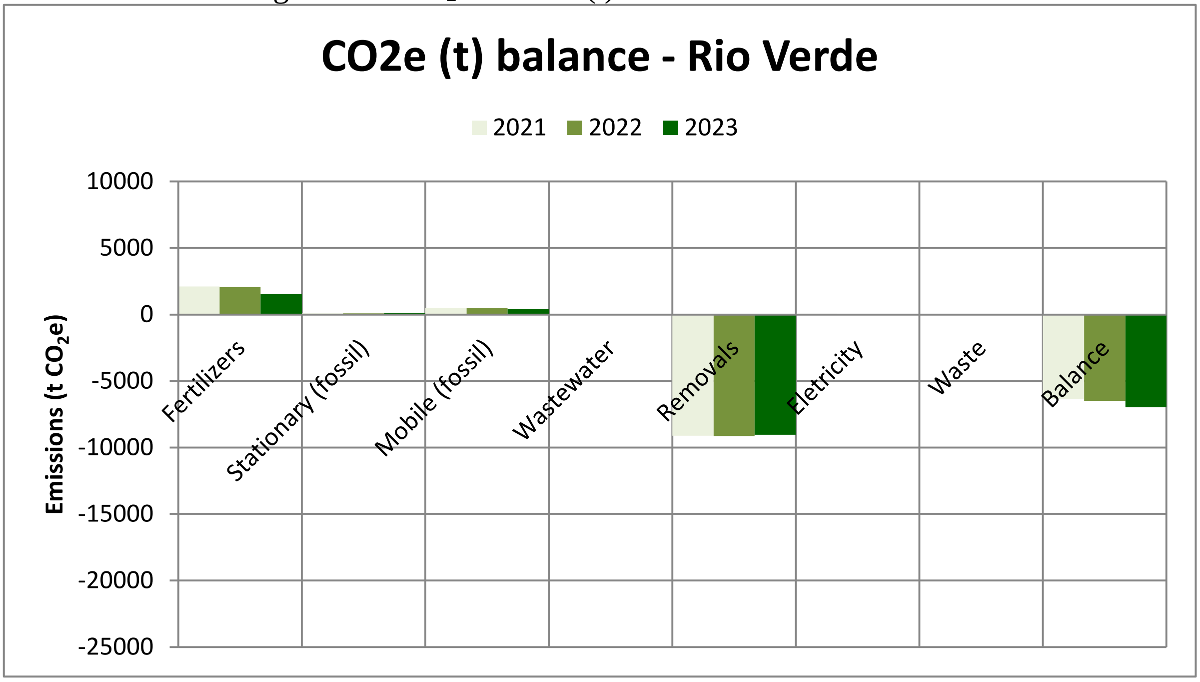
The CO_2e balance of the Capoeirinha unit is shown below (Figure 33):

Figure 33 – CO_2e balance (t) of the Capoeirinha unit



The CO_2e balance of the Rio Verde unit is shown below (Figure 34):

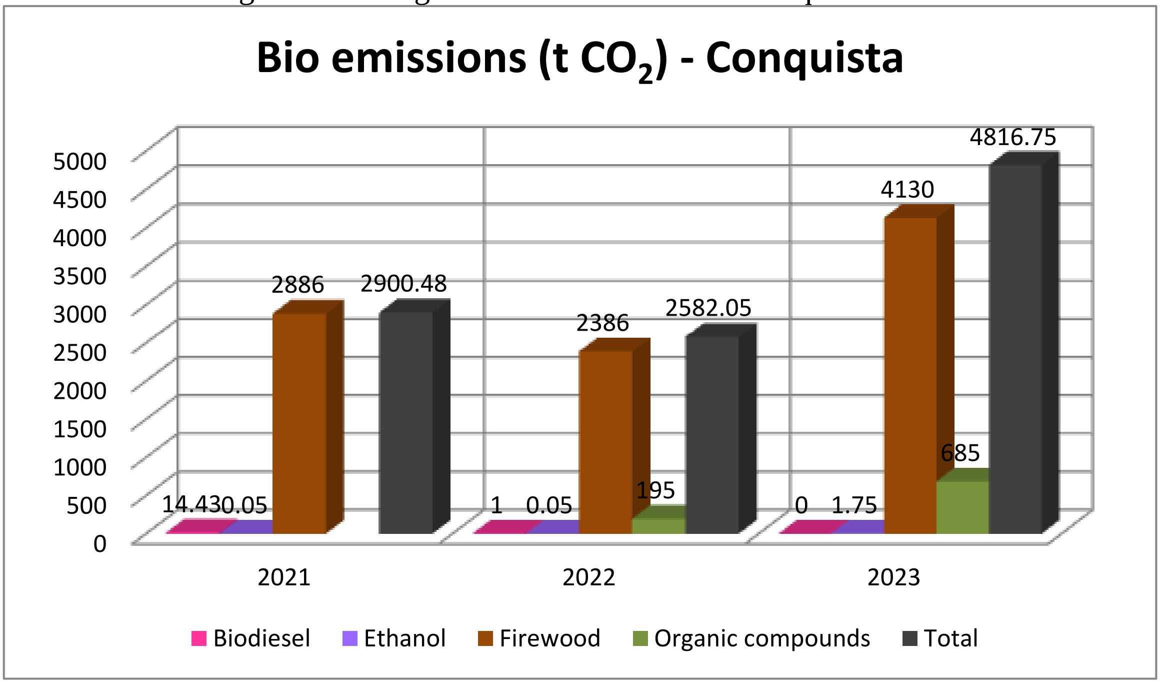
Figure 34 – CO_2e balance (t) of the Rio Verde unit



2.9 BIOGENIC EMISSIONS (SCOPE 1)

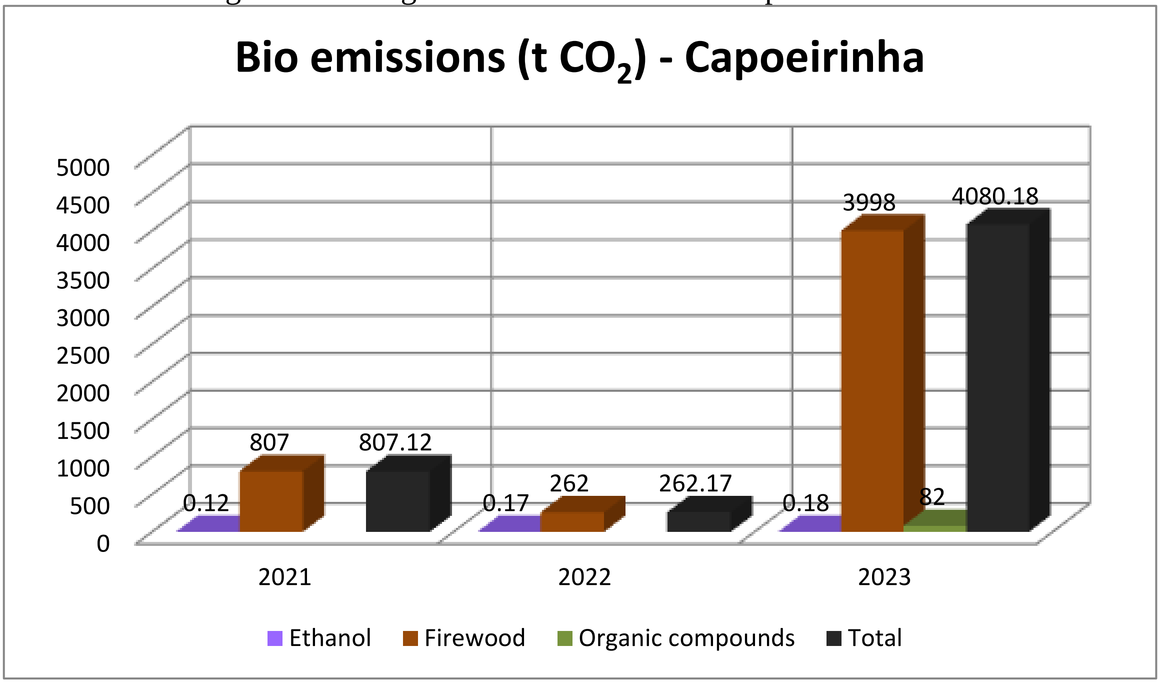
Biogenic emissions were reported per unit. Conquista's emissions are shown below in Figure 35:

Figure 35 – Biogenic emissions from the Conquista unit



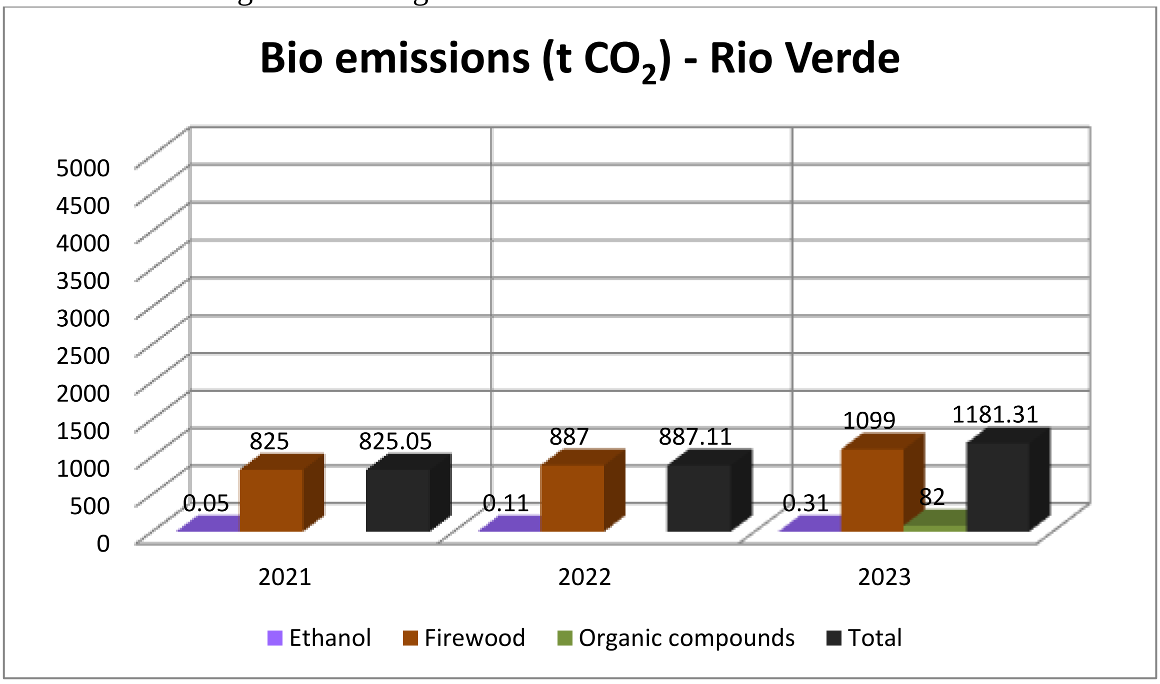
The biogenic emissions from Capoeirinha are shown below in Figure 36:

Figure 36 – Biogenic emissions from the Capoeirinha unit



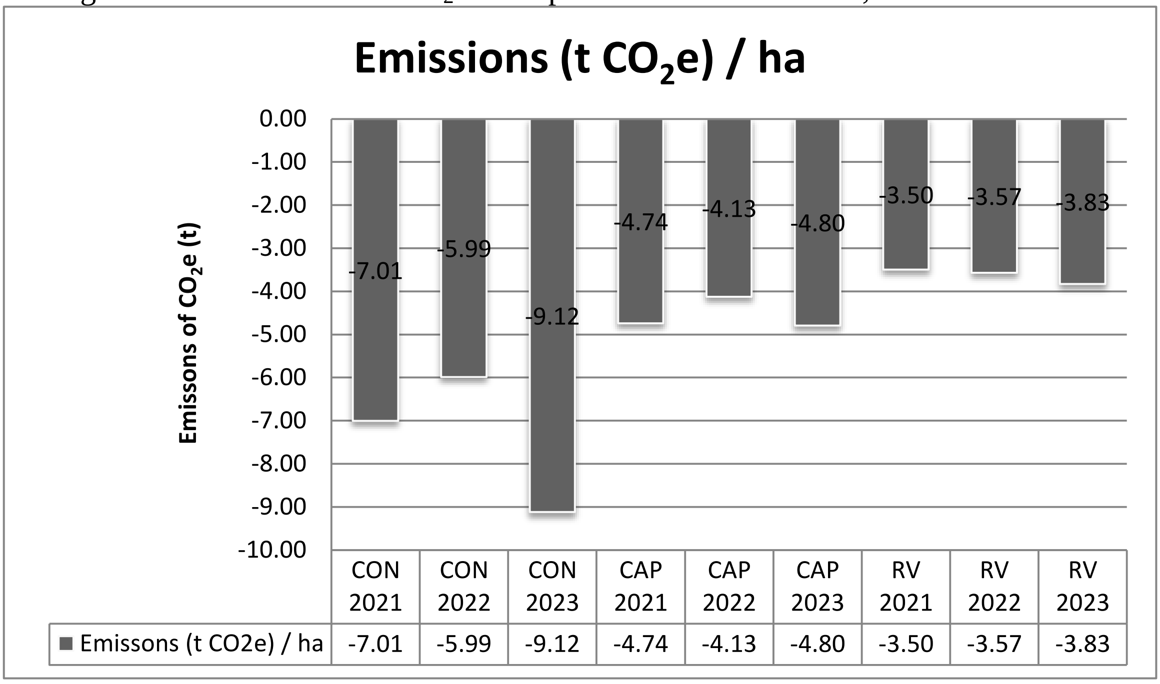
Rio Verde's biogenic emissions are shown below in Figure 37:

Figure 37 – Biogenic emissions from the Rio Verde unit



Below in Figure 38 we have the emission per ha in the study areas:

Figure 38 – Emissions in t CO_2e/ha in production units in 2021, 2022 and 2023



2.10 DISCUSSION

The highest emissions result from the use of synthetic and organic nitrogen fertilizers, limestone and agricultural gypsum. Among these, those fertilizers whose N comes from urea. This happens because urea contains C in its formulation, emitting CO_2 directly, and also due to the higher concentration of N. Fertilizers that do not contain urea emit only N_2O, which considerably reduces the emission of equivalent CO_2 in the end. Based on the methods adopted, the global warming potential of N_2O can be 265 to 298 times greater (GWP-100) than that of CO_2, which amplifies the total emission.

The direct burning of firewood in boilers and the consumption of fossil fuels, especially diesel oil, also contribute to the increase in GHG emissions. The highest biogenic emissions from firewood occur at Fazenda Conquista due to the greater quantity of material used.

Over the years analyzed, the highest GHG emissions from the Conquista Unit came from synthetic nitrogen fertilizers. This fact can be explained by the large amount of fertilizers used in coffee production, mainly N-P-K compounds. The

Conquista Unit is also responsible for the flow of production; the bags of coffee are transported from the other Units to Conquista and then on to the Port of Santos for export. Therefore, the consumption of fossil fuels is also high and, consequently, the emission of GHGs. The largest emissions in the Capoeirinha and Rio Verde Units come from the use of synthetic nitrogen fertilizers. These fertilizers are essential for the development of plants.

In relation to removals, all units are removing more CO_2 than they are emitting, especially the coffee areas. It is worth mentioning that, although the forest has a larger stock of C in the soil, annually, according to the data available, CO_2 removal was higher. This fact can be explained by: i) the consolidation stage of the forest areas, with ages over 40 years or close to that, stabilizing the removal of C, with the net removal rate being higher in areas of constant growth; ii) coffee, as a perennial plant, actively removes carbon more frequently during its growth process; and iii) coffee areas require more agricultural management, such as pruning, increasing the levels of biomass renewal and C accumulation; compared to forests, annual wood growth is lower. However, in the long term, forests remove a greater amount of CO_2 due to i) the greater accumulation of living biomass; ii) less periodic removal of biomass, since coffee and other agricultural crops are subject to human interference, such as pruning and weeding; and iii) the heterogeneity of species and ages, thus promoting a diversified removal of C.

Regarding the stock of C in the soil, this was carried out only in coffee areas, since field data were only obtained for this agricultural crop. The stocks were not accounted for in emissions/removals, but rather merely as an indicator of the values to give greater robustness to the work. In the future, it is recommended that soil samples be collected from forest and eucalyptus areas to compare the C stocks of these uses with coffee cultivation.

The results show that the study areas are removing more CO_2 from the atmosphere, with a negative C balance of emissions of -7.37, -4.55 and -3.63 tCO_2e/ha in the Conquista, Capoeirinha and Rio Verde units, respectively.