UNIVERSIDADE ESTADUAL PAULISTA - UNESP

CÂMPUS DE JABOTICABAL

TEMPORAL VARIABILITY OF ATMOSPHERIC CO2 AND CONTROL FACTORS OVER LARGE MANAGED AND DEGRADED PASTURE AREAS IN THE BRAZILIAN CERRADO

Marcelo Odorizzi de Campos

Agronomic Engineer

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Marcelo Odorizzi de Campos
Advisor: Prof. Dr. Newton La Scala Junior

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AUTOR: MARCELO ODORIZZI DE CAMPOS

ORIENTADOR: NEWTON LA SCALA JUNIOR

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Prof. Dr. NEWTON LA SCALA JUNIOR (Participaçao Virtual)
Departamento de Engenharia e Ciencias Exatas DECEx / FCAV UNESP Jaboticabal

Gustavo André de Araújo Santos.

Prof. Dr. GUSTAVO ANDRE DE ARAUJO SANTOS (Participaçao Virtual)
Porto Franco/MA / Insituto Federal de Educação, Ciência e Tecnologia do Maranhão - IFMA

Prof. Dr. ALAN RODRIGO PANOSSO (Participaçao Virtual)
Departamento de Ciências da Produção Agrícola / FCAV / UNESP - Jaboticabal

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AUTHOR'S CURRICULUM DATA

Marcelo Odorizzi de Campos – Born in Cândido Mota, in the interior of the São Paulo state, on 05/22/1995, son of José Valentim de Campos and Alba Tereza Odorizzi. He is currently an Academic Master's student at the Graduate Program in Agronomy (Vegetable Production) (CAPES 6) at Universidade Estadual Paulista Júlio de Mesquita Filho (UNESP), Faculdade de Ciências Agrárias e Veterinárias (FCAV) campus de Jaboticabal/SP, working with the modeling of atmospheric CO_2 levels, soil carbon stock, climatic and vegetative indices on degraded pastures managed, through the project: "Atmospheric CO_2, vegetation, soil carbon stock and climatic factors over-managed and degraded pastures in central Brazil". He completed his degree in Agronomic Engineering in 2020 from the same University (UNESP/FCAV). He was an intern in 2020 at CENTRO DE TECNOLOGIA CANAVIEIRA (CTC), working in the Research and Development (R&D) team, working mainly on Conventional Genetic Improvement (CGM) and on the Improvement of Genetically Modified Organisms (GMOs) in the sugarcane crop. In 2019, he was awarded a scholarship as a Research Assistant by the company Dow Agrosciences studying the "Changes in the Weed Community of the Enlist System" (Soybean, Corn, Wheat and Sorghum). In the same year, he participated in the research and elaboration team of the PROJETO RONDON selected in the Selection Process of Operação Vale do Acre 2019. He received a scholarship in 2018 from the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP - 2017/03188-1) developing the Research project: "Survey and Characterization of Family Farmers' Organizations in the EDRs of Jaboticabal, Ribeirão Preto and Barretos". Participated in four opportunities for Rural Extension projects, seeking to help the production of food and sustainable cultivation systems aimed at Family Agriculture.

DEDICATION

I dedicate it to my father José Valentim de Campos, my mother Alba Tereza Odorizzi, and my brothers Matheus Odorizzi de Campos and Luan Alberto Odorizzi dos Santos. Here I express my sincere affection to Prof. Dr. Luan Odorizzi for being the first graduate, master and doctor of my entire family, the pioneer of science who opened the doors to new horizons in my professional career.

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SUMMARY

LIST OF FIGURES

TEMPORAL VARIABILITY OF ATMOSPHERIC CO2 AND CONTROL FACTORS OVER LARGE MANAGED AND DEGRADED PASTURE AREAS IN THE BRAZILIAN CERRADO

Abstract: Anthropogenic changes in land use have contributed to an increase in the concentration of greenhouse gases (GHGs) in the atmosphere. Changing this scenario requires actions able to minimize emissions and remove carbon from the atmosphere. The stock of soil organic matter can be used as a carbon sink, in addition to reducing emissions, it also improves physical, chemical and biological aspects of the soil. Sequestering carbon in the soil represents 25% of the planet's natural potential to solve climate problems, whereas 60% refer to the recovery of previously lost stocks, and 40% to the protection of carbon already stored. Based on the hypothesis that degraded (DP) and managed (MP) pasture systems show contrasting vegetative indices and carbon levels stored in the soil, this study aimed to understand the temporal dynamics of atmospheric CO_2 concentration and other control factors on DP and MP in the Brazilian Cerrado biome. Using remote sensing tools and a 6-year historical series, was characterized under the areas atmospheric concentrations of CO_2 (xCO2), soil carbon stock (SCS t/ha – mean 0 a 0.30 m), vegetative characteristics (SIF – solar-induced chlorophyll fluorescence, NDVI – normalized difference vegetation index and LAI – leaf area index) and climatic aspects (LST Amplitude – land surface temperature amplitude and precipitation). Pearson's correlation showed that vegetative variables and precipitation are negatively related, and LST Amplitude and SCS are positively related to xCO2. It was also observed that LST Amplitude stood out as a potential new variable of direct impact on soil CO_2 emissions, as well as an auxiliary tool for distinguishing degraded and managed pastures. Except for xCO2, the hypothesis tests (Student t-test $p<0.05$) demonstrated that the MP were significantly different from the DP. Thus, MP showed to receive higher vegetative indices and precipitation volumes, however, lower LST Amplitude values. Linear regression analyzes ($p<0.001$) showed that SCS values impacted atmospheric CO_2 concentration only on DP. This result highlights the importance of pasture management as a way to protect and stabilize the carbon on this agricultural activity. Thus, it was possible to conclude that DP with carbon stored in the soil are the main sources of CO_2 for the atmosphere, when compared to MP. Therefore, degraded pastures with organic carbon stock in the soil will gradually lose their compartments, if not managed, due to carbon exposure to microbiological metabolism and the vegetative inability of plants to replenish soil compartments.

Keywords: Climate changes, Nature-based Solutions, Remote sensing, OCO-2, SoilGrids, Land Surface Temperature.

Resumo: As mudanças antrópicas no uso da terra têm contribuído para o aumento da concentração dos gases de efeito estufa (GEEs) na atmosfera. Mudar esse cenário requer ações capazes de minimizar emissões e retirar carbono da atmosfera. O estoque de matéria orgânica do solo pode ser usado como sumidouro de carbono, além de reduzir as emissões melhora também aspectos físicos, químicos e biológicos do solo. Sequestrar carbono no solo representa 25% do potencial natural do planeta em solucionar as questões climáticas, dos quais, 60% referem-se à recuperação dos estoques anteriormente perdidos, e 40% pela proteção do carbono já armazenado. Partindo da hipótese de que, sistemas de pastagens degradadas (DP) e manejadas (MP) demonstram índices vegetativos e níveis carbono estocado no solo contrastantes, este estudo objetivou compreender a dinâmica temporal da concentração de CO_2 atmosféricos e outros fatores de controle sobre DP e MP no bioma do Cerrado brasileiro. Utilizando ferramentas de sensoriamento remoto e série histórica de 6 anos, foi caracterizado sob as áreas concentrações atmosféricas de CO_2 (xCO2), estoque de carbono no solo (SCS (t/ha – médio 0 a 0.30 m), características vegetativas (SIF – fluorescência da clorofila induzida pelo sol, NDVI – índice de vegetação por diferença normalizada e LAI – índice de área foliar) e aspectos climáticos (LST Amplitude – temperatura da superfície terrestre amplitude e precipitação). A correlação de Pearson demonstrou que variáveis vegetativas e precipitação se relacionam negativamente, e LST Amplitude e SCS se relacionam positivamente com o xCO2. Foi observado também que LST Amplitude se destacou como potencial nova variável de impacto direto nas missões de CO_2 do solo, bem como, ferramenta auxiliar para distinção de pastagens degradadas e manejadas. Exceto para o xCO2, os testes de hipótese (Teste t de Student $p<0.05$) demonstraram que os MP foram significativamente diferentes dos DP. Assim, MP demonstrou receber maiores índices vegetativos e volumes de precipitação, entretanto, menores valores de LST Amplitude. As análises de regressão linear ($p<0.001$) exibiram que os valores de SCS impactaram a concentração atmosférica de CO_2 apenas sobre DP. Este resultado destaca a importância do manejo das pastagens como forma de proteger e estabilizar o carbono sobre esta atividade agricola. Assim, foi possível concluir que DP com carbono estocado no solo são as principais fontes de CO_2 para atmosfera, quando comparados aos MP. Portanto, pastagens degradadas com estoque carbono orgânico no solo irão gradativamente esvaziar seus compartimentos, se não manejados, devido a exposição do carbono a metabolização microbiológica e a incapacidade vegetativa das plantas em reabastecer os compartimentos do solo.

Palavras-chave: Mudanças Climáticas, Soluções Baseadas na Natureza, Sensoriamento remoto, OCO-2, SoilGrids, Temperatura da superfície do solo.

CHAPTER 1 – GENERAL CONSIDERATIONS

1.1. Introduction and Justification

Atmospheric concentrations of greenhouse gases (GHGs) have increased to alarming levels in recent decades (IPCC, 2021). The levels of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) reached 144%, 256% and 121% compared to pre-industrial levels, respectively (IPCC, 2021). Such atmospheric concentrations of GHGs raise the average temperature of the planet, intensifying global climate problems that more severely impact poor countries and social classes (DANGAL et al., 2017; PARRA et al., 2019).

Agriculture is an important source of CO_2, CH_4 and N_2O to the atmosphere. Worldwide, according to IPCC (2021), agriculture accounts for 11%, 47% and 58% of the planet's total anthropogenic emissions, respectively. The increase in CO_2 is mainly attributed to the large-scale use of fossil fuels (SCHIMEL; STEPHENS; FISHER, 2015). However, the planet has other important sources of CO_2, such as deforestation and changes in land use, contributing around 20% of the total (SCHIMEL; STEPHENS; FISHER, 2015).

In contrast to the high potential for emission, the agriculture is also considered an important tool for sequestering CO_2 (BANWART et al., 2014; WOOD; BAUDRON, 2018). Soil organic carbon (SOC) is by nature a stock of atmospheric CO_2, capable of becoming a carbon sink when managed for this purpose (BOSSIO et al., 2020). Protecting and restoring soil organic matter produces fundamental benefits for agricultural crops, as well as the ecosystem as a whole (BOSSIO et al., 2020; CONCEIÇÃO et al., 2017).

Occupying 20% of the national territory, pastures are the main responsible for feeding the cattle herd in Brazil, both for beef and for milk (BERNARDINO DIAS-FILHO, 2017; PARENTE et al., 2019). Brazilian beef production has a commercial herd close to 217 million animals in 2020, making the country the largest exporter of these commodities in the world (EMBRAPA, 2021).

According to MapBiomas (2022), of the total pastures in the national territory in 2020, about 14% are characterized as severely degraded pastures, 38% are moderately degraded and 48% are not degraded. It is estimated that in the Brazilian Cerrado, about 30 million hectares of pasture show some stage of degradation (SOARES et al., 2020).

In addition to low animal productivity, inadequate pasture management also increases GHG emissions per kilogram of milk and/or meat produced (BERNARDINO DIAS-FILHO, 2017). Thus, it is worth noting that degraded pastures contribute to increased soil carbon losses, due to the reduction in the quantity and quality of added organic matter, compromised by the low development of plants on their surface (IPCC, 2021; BOSSIO et al., 2020; MOITINHO et al., 2015).

Due to the vast Brazilian territory and the expressive volume of pastures, tools capable of capturing vegetative and climatic attributes over time of large territorial extensions are of great importance (PACHECO; CHAVES; NICOLI, 2013). Thus, the use of technologies such as remote sensing from satellites, can help the characterization of great areas and facilitate decision-making processes of the public authorities and the application of public policies, such as the ABC Program (Agricultura de Baixo Carbono) (OBERVATÓRIO DO PLANO ABC., 2016; PAN; XU; MA, 2021).

Thus, having demonstrated the importance of pastures for mitigating climate change and its significant presence in the national territory, studies capable of understanding the GHG emission of these areas are important. Therefore, this study sought to answer the following question: do the contrasting vegetative attributes of degraded and managed pastures impact the temporal variability of CO_2, soil carbon stock and climatic aspects, in large areas in the Cerrado biome, Brazil?

1.2. Literature Review

2.1.1. Climate Change

Agriculture is not only an emitter and potential store of atmospheric carbon, it is also a victim of global climate change processes (IPCC, 2021). According to the Intergovernmental Panel on Climate Change (IPCC), the agricultural sector will be strongly affected by global climate change (IPCC, 2019; 2021). In addition to dealing with climate impacts on production, it will also be necessary to ensure food security for a growing global population, often socially and economically vulnerable to climate change (IPCC, 2019; 2021).

For Bossio et al. (2020), Soil carbon has 25% of the global natural potential to solve climate problems. Of this amount, 40% comes from protecting carbon that has already been stored, and 60% through reincorporation into depleted soils (BOSSIO et al., 2020). This dual role of soil carbon in the global emissions budget demonstrates that climate benefits will be achieved when strategies that conserve stored carbon and restore stocks in depleted soils are adopted (SMITH et al., 2008).

Estimates reveal that the inappropriate use of natural resources developed agriculture throughout history has contributed about 55 to 90 billion tons (Pg) of carbon (ROBERTS; HESTER, 1972). In the Brazilian scenario, the sector of changes in land use and forests, has even greater relevance for the country's emissions, exceeding the mark of 70% of the total CO_2 equivalent (SEEG, 2021). On the other hand, worldwide agriculture and pastures are considered as potential sequesters of CO_2 from the atmosphere, with about 50% of the sequestering potential (BOSSIO et al., 2020; VALADÃO et al., 2015; ABDALLA et al., 2018).

Such considerations make it necessary to sustainably align paradigms of an agriculture that historically disfavors the positive balance of the physical, chemical, biological properties of the soil (BOSSIO et al., 2020; CONCEIÇÃO et al., 2017; DE AZEVEDO et al., 2018). Thus, storing carbon in the soil does not respond only to climatic benefits, but also to productive, economic, social and ecological benefits (IPCC, 2019; 2021; ABDALLA et al., 2018; CONCEIÇÃO et al., 2017). Protecting and increasing soil carbon storage also helps: (1) increase or maintain soil fertility, (2) promote resilience to climate change, (3) reduce soil erosion, (4) and delay or halt desertification processes (BOSSIO et al., 2020; ABDALLA et al., 2018; TAVANTI et al., 2020; BERNARDINO DIAS-FILHO, 2017).

In addition to food production, it is worth highlighting the due alignment of these practices with global and national agreements and policies involving the theme. As in the case of the United Nations Convention to Combat Desertification (UNCCD), United Nations Framework Convention on Climate Change (UNFCCC), and the United Nations Sustainable Development Goals (SDGs), especially for the 13th objective: “Action Against Global Climate Change” (SMITH et al., 2019; LAL, 2004).

There are many directions of the Sustainable Development Goals that fit the theme. For the environmental dimension, it can highlight Responsible Consumption and Production (12) and Action Against Global Climate Change (13). In the social dimension, Zero Hunger and Sustainable Agriculture (2) stand out, and for the economic dimension Decent Work and Economic Growth (8) (ONU, 2022).

2.1.2. Brazilian pastures: dimensions and sequester carbon opportunities

Agriculture and combating climate change need to align their goals (SMITH et al., 2019; LAL, 2004). Due to the high agricultural export of food commodities and the way in which some of them are produced, Brazil had to adopt measures to minimize their interference with the climate (BERNARDINO DIAS-FILHO, 2017). The last few years have shown significant demands from global trade for more effective actions around deforestation, support for traditional communities and more sustainable agriculture (LEITE-FILHO et al., 2021).

In 2009, at the UNFCCC COP 15 (15th Conference of the Parties to the United Nations Framework Convention on Climate Change) in Copenhagen, Brazil has committed to reducing gas emissions, mitigating between 975 million and 1 billion tons of CO_2 by 2020 (CONCEIÇÃO et al., 2017). In 2015, through the commitment to the NDC (Nationally Determined Contributions) signed in Paris (UNFCCC COP21), it was assumed that by 2030 it would recover more than 15 million hectares of degraded pastures, using among other technologies the Crop Livestock Forest Integration Systems (ILPF) (CONCEIÇÃO et al., 2017; LEITE-FILHO et al., 2021).

To enforce this agreement, the Brazilian government has prepared some adaptation and mitigation plans for some sectors of the economy (OBERVATÓRIO DO PLANO ABC., 2016; CONCEIÇÃO et al., 2017). Of the seven programs proposed, six of them are related to agricultural management tools for mitigation: No-tillage System (SPD); Biological Nitrogen Fixation (FBN); Recovery of Degraded Pastures (RPD); Agroforestry Systems (SAF); Crop Livestock Forest Integration Systems (ILPF); Planted Forests (FP); e Treatment of Animal Waste (TDA) (CONCEIÇÃO et al., 2017).

In this context, as demonstrated by Abdalla et al. (2018); Figueiredo et al. (2017), the recovery of degraded pastures is a strategic point. Low carbon stocks in soil surface horizons, low fertility, high acidity, and surface compaction are characteristic of degraded pastures (BERNARDINO DIAS-FILHO, 2017). However, in practice, even with scientific consensus on its potential, the expressive volume of degraded pastures in Brazilian territory limits the storage of carbon for climate mitigation (VALADÃO et al., 2015).

Overall, the last two decades have seen the emergence of a variety of robust methodological approaches to calculate mitigation benefits in agricultural areas, grasslands, savannas, peatlands and coastal wetlands (PARENTE et al., 2019; SOMKUTI et al., 2021; VICENTINI et al., 2019; ZHANG et al., 2014). Seeking to assist research involving the role of carbon in the soil in its various benefits, the SoilGrids250m 2.0 platform can be highlighted (SOILGRIDS, 2022). This tool provides several aspects of the soil, such as carbon stock, nitrogen stock, texture and others, as well as maps from data collected in fields, of 75 covariates related to soil formation factors (HENGL et al., 2014, 2017; POGGIO et al., 2017).

Figure 1 shows a spatial clipping of Brazil and its biomes, based on the average soil organic carbon stock (t/ha), for a depth of 0 – 0.30 m (SOILGRIDS, 2021). The estimate of accuracy attributed to SoilGrids can vary from 1 to 23 km, depending on the concentration of information collected “in loco”, close to the location published by surveyors from all over the globe (HENGL et al., 2014, 2017; POGGIO et al., 2017).

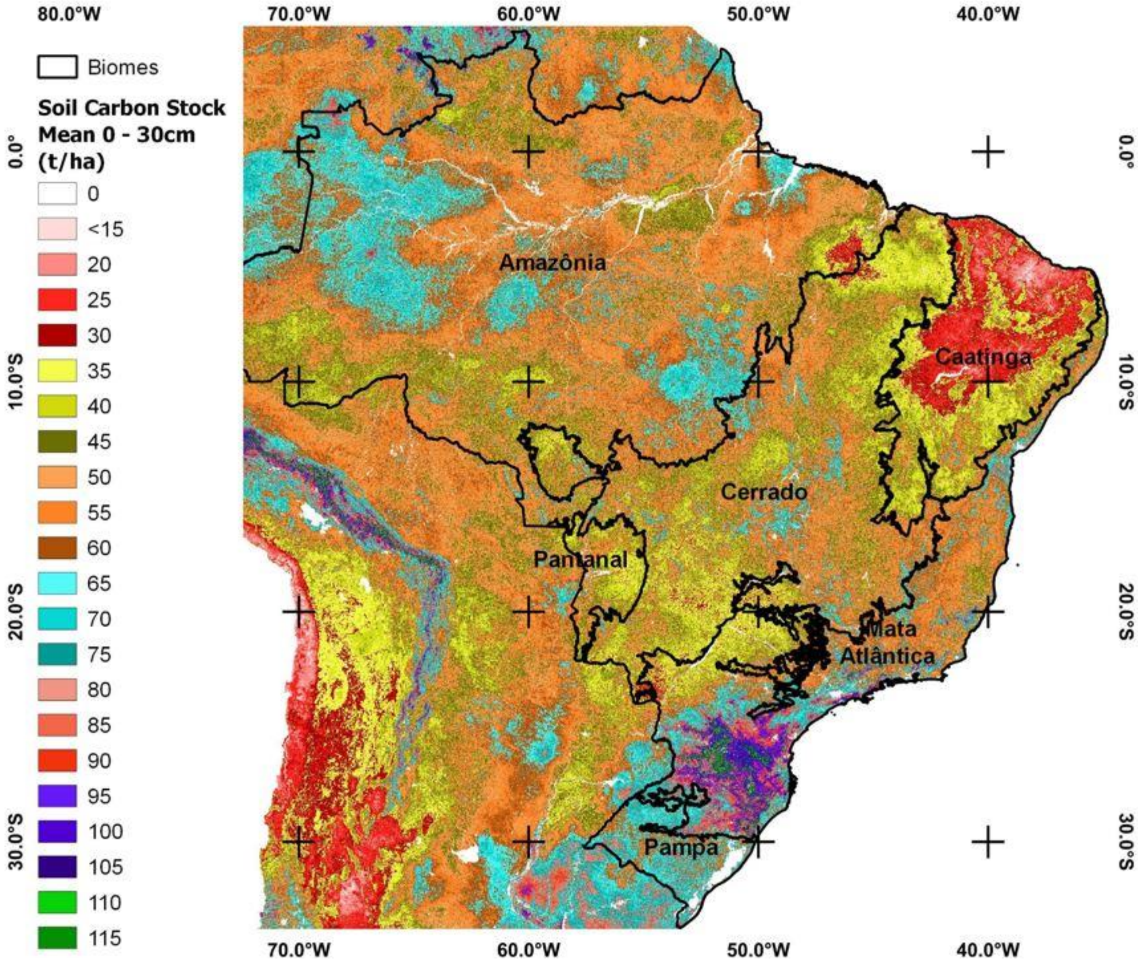

Figure 1. Mean Stock of Organic Carbon in Soil (0 – 0.30 m): SoilGrids250m 2.0 Plataform.

In the soil environment, CO_2 is moved through two mechanisms: (1) displacement by diffusion, going from the most concentrated to the least concentrated region; and (2) displacement by convection, which moves from the air flow distributed by the pressure gradient (BALL et al., 1997). These factors can vary according to the texture, water content, structuring, temperature and humidity of the soil environment (BALL et al., 1997).

Such dynamics occur respecting the biological aspects of thousands of living organisms that coexist in the soil environment. The respiration of these organisms, comprised of bacteria, fungi, arthropods, micro and macrofauna, roots, and others, emit CO_2 into the atmosphere (CHAPLOT; COOPER, 2015).

Especially soil bacteria and fungi, release CO_2 when they metabolize carbon stored as organic material from plant and animal waste, deposited in the soil by the environment (CHAPLOT; COOPER, 2015; LAL, 2009).

Thus, differences in soil type, temperature, humidity, population density of microorganisms in the rhizosphere and changes made by management interfere in the spatio-temporal dynamics of soil CO_2 flux. Therefore, it is important to understand the carbon stock potential of the contrasts observed between degraded and managed pastures, studying them from the perspective of temporal variability (DILUSTRO et al., 2005).

2.1.3. Remote sensing and carbon cycle

Working to improve and facilitate access to information in recent years, some satellites were sent into space with the mission of helping to quantify several variables, mainly those related to global climate change issues (KASUYA et al., 2009; BOVENSMANN et al., 1999; O'DELL et al., 2012). Examples are the GOSAT, SCIAMACHY and OCO-2 satellites, important for the quantification of the average concentrations of the atmospheric column of CO_2 and methane (CH_4) (KASUYA et al., 2009; BOVENSMANN et al., 1999; O'DELL et al., 2012).

Satellites such as OCO-2 and TERRA/AQUA provide data on important vegetative and climatic variables, making it possible to build relationships between these and atmospheric GHGs (AppEEARS, 2021, NASA OCO-2, 2022). For example, the solar-induced chlorophyll fluorescence (SIF), which aims to quantify the solar radiation reflected by the object studied, that is, the photosynthetic capacity of pastures (MOHAMMED et al., 2019; NASA OCO-2, 2022). As well as the Normalized Difference Vegetation Index (NDVI), which aims to determine the vegetation cover of the crop, therefore, vegetative aspects of pastures (DA SILVA QUINAIA et al., 2021; PARENTE et al., 2019; VALLE JÚNIOR et al., 2019).

Services such as those provided by Atlas Digital das Pastagens Brasileiras (LAPIG - Laboratório de Processamento de Imagens e Geoprocessamento) made possible by using remote sensing, help studies related to pastures in Brazil, especially in a scenario of rapid changes and large territorial dimensions (LAPIG, 2022). This platform provides a historical series of pasture maps, organized into 33 maps containing records from 1985 to 2017 (PARENTE et al., 2019). This tool has data related to total pasture areas in the country, as well as pasture areas at different levels of degradation (LAPIG, 2022).

In order to better visualize their contributions, Figure 2 shows the spatial distribution at the Brazilian level: (A) the set of pasture classes provided by the LAPIG platform in 2019; and (B) polygons developed to group pixels of degraded (DP) and managed (MP) pastures (LAPIG, 2022).

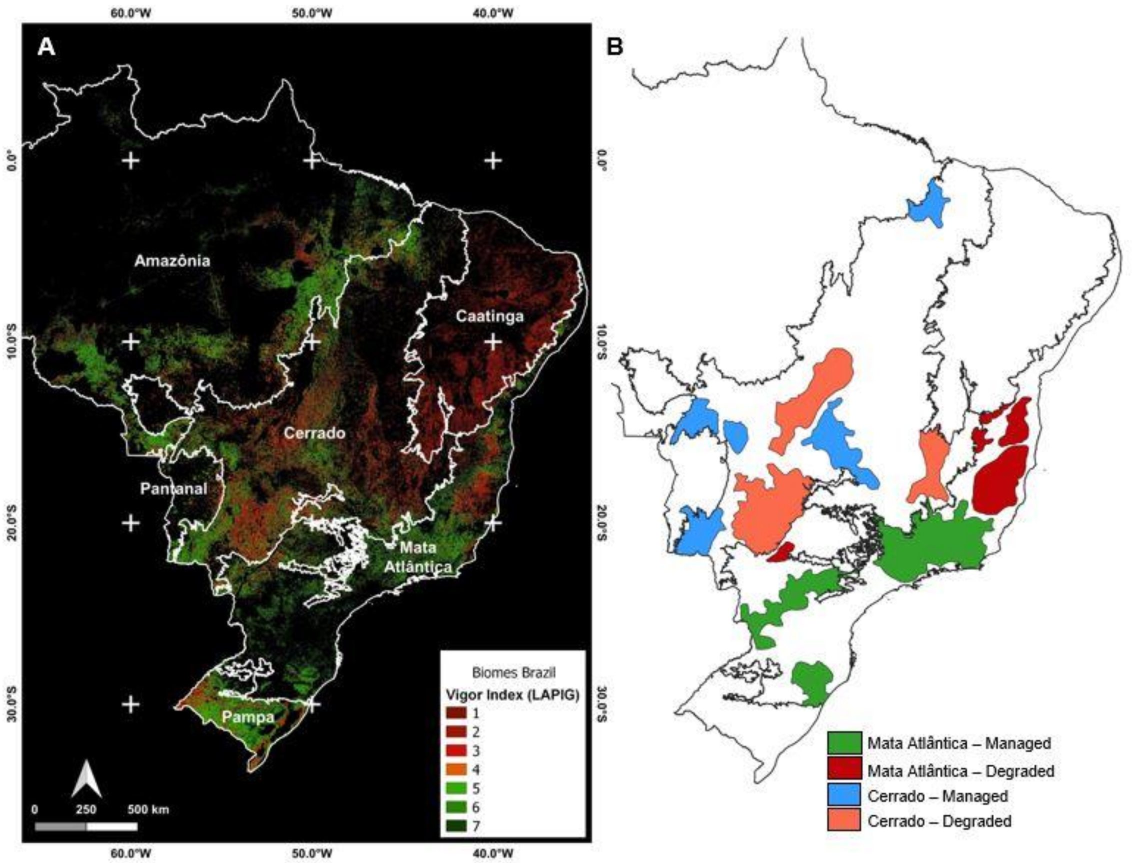

Figure 2. Classes of Pastures in Brazil: (A) Image Processing and Geoprocessing Laboratory (LAPIG); e (B) discontinued initial characterization of polygons related to degraded and non-degraded pasture clusters, for Atlantic Forest and Cerrado.

More than producing food of great biological value, agricultural production systems such as well-managed pastures can benefit environmental and economic aspects, reducing the national emission GHG (PACHECO; CHAVES; NICOLI, 2013). In addition, contribute to reducing the carbon footprint of meat production, Brazil's main commodity in the international food market (PACHECO; CHAVES; NICOLI, 2013).

1.3. General goals

Therefore, demonstrating the importance of the theme for the world and national scenario, as well as the tools involved in the scientific production of this area of knowledge, the present study was based on the hypothesis that degraded (DP) and managed (MP) pasture systems show contrasting vegetative indices and carbon levels stored in the soil, this study aimed to understand the temporal dynamics of atmospheric CO_2 concentration and other control factors on DP and MP in the Brazilian Cerrado biome. Thus, was aimed to: (i) understand the space-time dynamics of atmospheric CO_2 in contrast between pastures degraded and managed in central Brazil; and (ii) understand the impact of pasture management on CO_2 control factors, such as climatic aspects, vegetative characteristics and soil carbon stock.

CHAPTER 2 – ATMOSPHERIC CO_2, VEGETATION, SOIL CARBON STOCK AND CLIMATIC FACTORS OVER-MANAGED AND DEGRADED PASTURES IN CERRADO BRAZIL

Abstract: Brazil has 167.7 million hectares of pastures, 71% (119 million hectares) of which is in some degree of degradation. Besides the low animal support capacity and vegetative yield, degraded pastures also contribute significantly to soil and vegetation carbon losses, through CO_2 emission. This study sampled important aspects in contrasting degraded (DP) and managed (MP) pastures in central Brazil: the column-average concentration of carbon dioxide in the atmosphere (xCO2), Soil Carbon Stock (SCS), as well as Solar-induced Chlorophyll Fluorescence (SIF), Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) as vegetative characteristics, and Land Surface Temperature Amplitude (LST Amplitude) and Precipitation as climatic aspects. Except for xCO2, MP was significantly different (Student t-test $p < 0.05$) from DP with higher SIF, NDVI, LAI, Precipitation, and SCS, but smaller LST Amplitude. Our results indicate higher Precipitation and SCS in MP when compared to DP due to its positive effect of higher vegetative values. Linear regression analyses ($p < 0.001$) indicate xCO2 negatively relates with the precipitation and vegetative variables (NDVI, LAI, and SIF), but positively with LST Amplitude and SCS. Soil carbon stored related positively with xCO2 in DP pastures only, suggesting soil carbon losses could be playing as a source of atmospheric CO_2 in those plots. Therefore, this study concludes that DP with carbon stored in the soil is the main source of CO_2 for the atmosphere when compared to MP. These areas, if not managers correctly, will lose the stocks organic carbon to the atmosphere as CO_2 and contribute directly to global warming. These findings may favor nature-based solutions indicating that proper pasture management is an important aspect to mitigate emissions and to improve soil carbon content helping to mitigate atmospheric CO_2.

Keywords: OCO-2, SoilGrids, LST, Remote sensing, Climate changes, Nature-based Solutions.

2.2. Introduction

The atmospheric levels of greenhouse gases (GHG) have increased in the last decades at worrying rates. According to the World Meteorological Organization (WMO) the levels of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) reached 144%, 256%, and 121% above pre-industrial levels, respectively (IPCC, 2021). Nowadays, agriculture is responsible for 11%, 47%, and 58% of the global total of CO_2, CH_4, and N_2O, respectively (IPCC, 2021).

According to the Greenhouse Gas Emissions and Removal Estimates System (SEEG), the land and forest use change sector is the largest emitter in the country, surpassing the 70% mark of total CO_2 equivalent emissions in some years (DE AZEVEDO et al., 2018). Occupying 166 million hectares, Brazilian pasture areas are considered strategic for this balance, especially considering CO_2 emission or sequestration, depending on the management adoption and productive scenario (ABDALLA et al., 2018; TAVANTI et al., 2020).

For instance, considering soil carbon management is critical to dealing with climate change as 25% of the planet's natural potential for climate solutions (total potential, 23.8 Gt CO_2 equivalent per year) is linked to soil carbon stocks (SCS) (BOSSIO et al., 2020). However, according to the Image Processing and Geoprocessing Laboratory (LAPIG) of the total pastures in Brazil, around 58.8% (97.7 million hectares) are in some degree of degradation and only 41.2% (68.7 million hectares) are not classified as degraded (PARENTE et al., 2019).

The degradation process of pasture is delimited as the decrease of vegetal capacity of the animal support, impacting directly the soil exposition and vigor plants (BERNARDINO DIAS-FILHO, 2017). In addition to the low animal support capacity and plant productivity, degraded pastures contribute to soil and vegetation carbon losses throughout CO_2 emission (ABDALLA et al., 2018; MENDES et al., 2021). Therefore, the agricultural management of pastures becomes essential to revert the current scenario. It is well known that pasture management could boost animal and plant productivity and be a strategic tool to increase and protect soil organic carbon (ABDALLA et al., 2018; BOSSIO et al., 2020; TAVANTI et al., 2020).

Recently some authors have demonstrated that the column-averages concentration of CO_2 in the atmosphere (xCO2) under different crops is impacted by vegetative factors, aspects directly modified by crops management (DA COSTA et al., 2021; MORAIS FILHO et al., 2021; SOMKUTI et al., 2021; YANG et al., 2021). In addition, Abdalla et al., 2018 and Tavanti et al., 2020 indicate the beneficial effect of agricultural management in pastures by reducing soil CO_2 emissions. Thus, understanding and contrasting the effects of pasture management on the CO_2 atmospheric dynamics becomes of great importance

(ABDALLA et al., 2018; MENDES et al., 2021; PARENTE et al., 2019; VALLE JÚNIOR et al., 2019).

Already are well known the aspects involved to degradation pasture, however, the new challenger has been recognized them on large scale (VALLE JÚNIOR et al., 2019). Due to the large territorial extension of Brazil and the area of pastures in its territory, research involving remote sensing to characterize pastures has gained relevance, mainly by applying NDVI to determine levels of degradation pastures (DA SILVA QUINAIA et al., 2021; PARENTE et al., 2019; VALLE JÚNIOR et al., 2019).

Thus, satellite monitoring of atmospheric concentrations of CO_2 can facilitate international climate treaties and policies, enabling emissions control and compliance with agreements, mainly from food production, meat footprint carbon, and earth use (PAN; XU; MA, 2021). The hypothesis of the work was: Pasture management affects the spatiotemporal dynamics of xCO2 and is related to vegetative and environmental factors of control. Therefore, the present study aimed to understand the temporal dynamics of contrast between degraded and managed pastures in center Brazil.

2.3. Material and Methods

2.3.1. Study area

Based on the quality pasture classification of Parente et al. (2019) 05 adjacent areas of pastures located in the Brazilian Cerrado biome were delimited (Fig. 3), Degraded Pasture 1 (DP1); Degraded Pasture 2 (DP2); Managed Pasture 1 (MP1); Managed Pasture 2 (MP2); and Managed Pasture 3 (MP3). Two of these areas concentrate mostly pixels (red) related to pastures classified as degraded (DP1 74.0% and DP2 77.1%), while 03 areas have pixel concentrations (green) mostly from pastures classified as managed (MP1 76.5%, MP2 74.8%, and MP3 63.0%).

Figure 3 presents the location of the studied areas North (longitude -56°28′23″ and latitude -14°22′44″); northeast (longitude -49°15′36 and latitude -11°51′36´´); south (longitude -53°30′4″ and latitude -22°19′43″); and southwest (longitude -57°2′19″ latitude -19°47′51″). The studied region has a climate defined as tropical, with two clear seasons, rainy summers and dry winters, predominantly Aw (tropical with dry winters) and Am (tropical with monsoons) (ALVARES et al., 2013).

This work was based on pasture classification developed by Parente et al. (2019). The author made the classification through Landsat image processing from machine learning methods (https://pastagem.org/map). From the Google Earth Engine, the totality of Brazilian pastures between the years 1985 to 2017 was analyzed and classified by the degradation status and management classes.

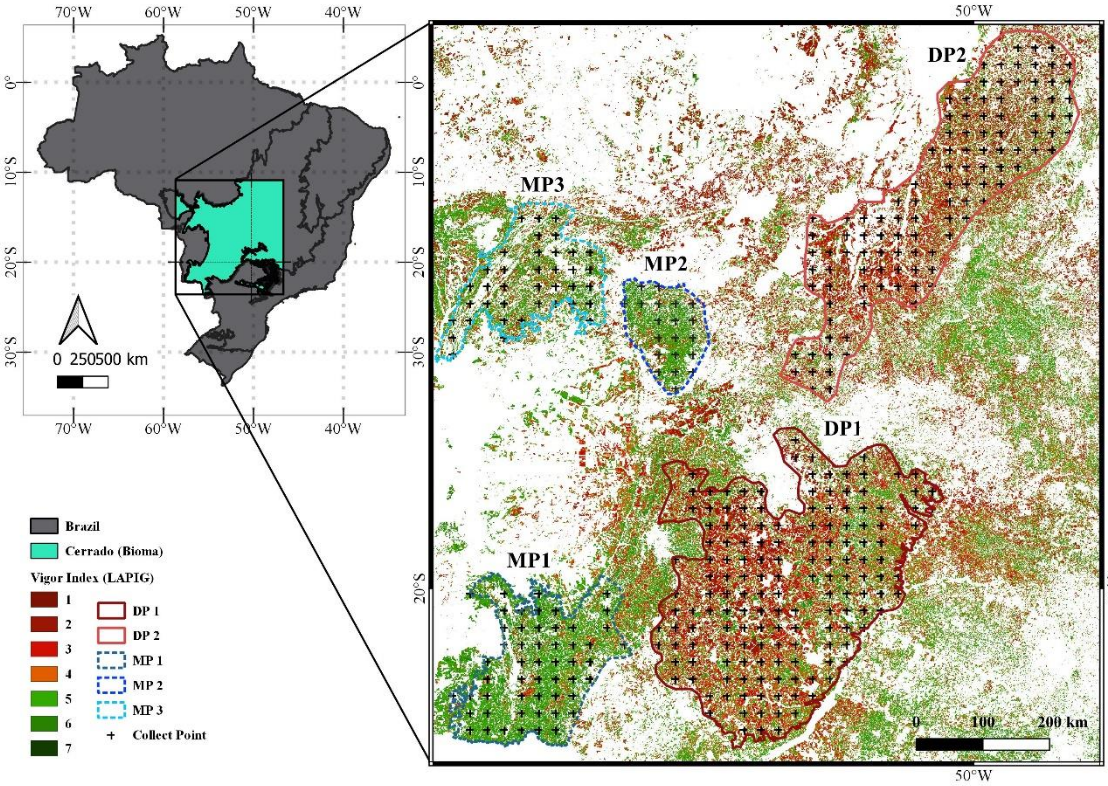

Figure 3. Brazil and part of the Cerrado biome, with emphasis on degraded pasture areas (DP1 dark red and DP2 light red), managed pasture (MP1 green, MP2 dark blue and MP3 light blue), and data collection points for each variable (**+**).

The degradation pasture can be delimited as the continued decrease of vegetal capacity of the animal support, impacting directly the soil exposition, plant vigor, and recuperation after grazing (BERNARDINO DIAS-FILHO, 2017). Thus, Parente et al. (2019) make use of the PVI (Pasture Vigor Index) as an indicator of the vigor of pastures. This factor varies between 0 and 1, where values close to 0 indicate pastures with lower plant vigor, while values close to 1 indicate pastures with greater vigor (PARENTE et al., 2019). This tool characterizes mainly the degradation vegetative of the pastures because the index used is relative to the vegetal vigor of the areas, but bring also aspects such as soil exposition and vegetal cover, fundamental features to understand the concentration CO_2 behavior under these areas (BERNARDINO DIAS-FILHO, 2017; PARENTE et al., 2019; VALLE JÚNIOR et al., 2019).

According to Parente et al. (2019), the initial PVI of pastures (intercept) was determined, evaluating and accounting for its trend (slope) along with the delimited historical determination, in order to determine the level of pasture vigor. The index was generated using 392 NDVI images. Linear interpolations were also applied to fill in missing data in the time series, as well as outlier removal and function STL (Seasonal Trend and Decomposition by Loess) to remove the seasonality vigor from pastures.

For the determination of data collection points (Collection points n°) the common geo-referenced locations were utilized (Table 1). Therefore, points of common longitudes and latitudes were used for all studied years. From these, the number of data acquisition points was obtained, relating to column average concentration of carbon dioxide (CO_2) in the atmosphere (xCO2), Solar-Induced chlorophyll Fluorescence (SIF), Normalized Difference Vegetation Index (NDVI), Leaf Area Index (LAI), Land Surface Temperature Amplitude (LST Amplitude).

Table 1
Characterization of the study area; degraded pasture 1 (DP1), degraded pasture 2 (DP2), managed pasture 1 (MP1), managed pasture 2 (MP2), and managed pasture 3 (MP3). Area (km^2) of the polygon, the concentration of pastures in percentage (Pasture %), and area (Pasture km^2), pastures by class (Degraded e Managed %), total collection points (Collection Points n°) and the average distance between collection points (Spacing Points km).

Polygon	**Area (Polygons)** (km^2)	**Pasture** (%)	**Pasture** (km^2)	**Pasture Degraded** (%)	**Pasture Managed** (%)	**Collection Points** n°	**Spacing Points** (km)
DP1	132347.5	67.2	88992.8	74.8	25.2	155	23.96
DP2	96179.0	55.3	53230.6	77.0	23.0	113	21.70
MP1	44349.8	65.7	29146.2	23.4	76.6	54	23.23
MP2	17210.8	61.4	10573.2	25.2	74.8	21	22.43
MP3	33271.0	50.0	16395.5	37.0	63.0	39	20.50
	Sum	Mean	Sum	Mean	Mean	Sum	Mean
DP	228526.5	61.2	142223.4	75.9	24.1	268	22.8
MP	94831.6	59.0	56114.9	28.5	71.5	114	22.0

The mean distance of the data (spacing points) was created by dividing the polygon area (Polygon Area km^2) and the number of collection points for the variables (Collection points n°). Thus, it was possible to develop common values to demonstrate the average distance between collection points (Spacing Points km) (Table 1).

2.3.2. Determination of xCO2, vegetative (SIF, NDVI, and LAI), and environmental (LST Amplitude and Precipitation) variables

For the temporal variability study, the historical series of 6 complete years was characterized from October 2014 to October 2020. The variables studied in the time series were the column-averages of CO_2 in the atmosphere (xCO2) (O'DELL et al., 2012) Solar-Induced chlorophyll Fluorescence (SIF) (FRANKENBERG et al., 2014), Normalized Difference Vegetation Index (NDVI) (VALLE JÚNIOR et al., 2019), Leaf Area Index (LAI), Land Surface Temperature Amplitude (LST Amplitude) (WAN, Z., S. HOOK, 2015; SIABI; FALAHATKAR; ALAVI, 2019) e Precipitation (STEINKE; MELO; STEINKE, 2017; DA COSTA et al., 2021; YU et al., 2019).

The xCO2 and SIF have a temporal resolution of 16 days, spaced 1 km apart, and may have failures of up to 2 km (Table 2). Both were collected from the OCO-2 platform (https://co2.jpl.nasa.gov/?mission=oco-2). For the SIF (W m^{-2} sr^{-1} um^{-1}) negative values were removed from the database, as they are considered as sensor capture errors, and later applied the correction for SIF 771 and SIF 757 (W m^{-2} sr^{-1} μm^{-1}) proposed by Yu et al. (2019), Equation 1 (Eq. 2).

$$SIF = \frac{SIF_{757} + 1.5\ SIF_{771}}{2} \qquad \text{(Eq.1)}$$

Where: SIF (W m^{-2} sr^{-1} μm^{-1}) represents the adjusted of Solar-Induced chlorophyll Fluorescence; SIF $_{757}$ is Solar-Induced chlorophyll Fluorescence at 757 nm; and SIF $_{771}$ is Solar-Induced chlorophyll Fluorescence at 771 nm.

The NDVI (0-1) e LAI (m^2/m^2) have a temporal resolution of 16 and 8 days, respectively, with spatialization of 0.5 x 0.5 (Table 2). Both were collected from the MODerate Resolution Imaging Spectroradiometer (MODIS-TERRA) (AppEEARS, 2021).

Table 2
Group of variables, sensors, platform and their respective temporal and spatial resolution.

Variable	Data	Source	Spatial resolution (km)	Temporal resolution (Days)
GHG	xCO2 (ppm)	OCO-2	1.0 x 2.25	16
Vegetation	SIF ($Wm^{-2} sr^{-1} \mu m^{-1}$)	OCO-2	1.0 x 2.25	16
	NDVI	MOD13.A1.006	0.5 x 0.5	16
	LAI (m^2/m^2)	MCD15.A2H.006	0.5 x 0.5	8
Climate	LST Amplitude (°C)	MOD11.A2.006	1.0 x 1.0	8
	Precipitation (mm)	ANA	0.25 x 1.0	1

The LST Amplitude (°C) is calculated from measurements of Infrared Spectral Thermals (IST) (MUTIIBWA; STRACHAN; ALBRIGHT, 2015), performed by MODIS-EARTH (APPEEARS, 2022). This variable can be calculated daily, but temporal resolutions of 8 days and spatialization of 1 km x 1 km were used for this study. For this calculation, day (LST Day) and night (LST night) Land Surface Temperatures were surveyed (ZHANG et al., 2014). Through the difference between these variables, monthly averages called Land Surface Temperature Amplitude (LST Amplitude) were elaborated, as shown in Equation 1 (Eq.2).

$$LST_{\text{Amplitude (°C)}} = \frac{\sum LST_{Day} - \sum LST_{Night}}{n} \quad \text{(Eq.2)}$$

Where: LST_{Day} is the ground surface temperature of the day; LST_{Night} is the ground temperature of the ground at night; and n is the number of monthly collections.

Land Surface Temperature and Emissivity (LST&E) are retrieved in 1 km pixels by the split-window algorithm (Table 2) (APPEEARS, 2022). The MOD11A2 product provides a temperature and emissivity of the land surface (https://lpdaac.usgs.gov/products/mod11a2v006/). Each pixel value is an average of all corresponding pixels in MOD11A1 LST collected within that period. In this algorithm, the surface emissivity in bands 31 and 32 is estimated through the types of land cover, air temperature, and column of water vapor (APPEEARS, 2022). In the day and night LSTs and emissivity are recovered from observations in seven TIR bands (APPEEARS, 2022).

Land surface temperature (LST) is a mixture of vegetation and bare ground temperatures. LST is the radiative temperature of the earth's surface, measured in the direction of the remote sensor. Its estimate also depends on the soil moisture, vegetation cover, and albedo (COPERNICUS GLOBAL LAND SERVICE, 2022; FREITAS et al., 2013; WAN, Z., S. HOOK, 2015). Authors as Acero and González-Asensio (2018) and Zhang et al. (2014) used the thermal amplitude of the soil surface to compare different seasons. However, for this study it was proposed to use the thermal amplitude in monthly averages from common georeferenced sampling points for day and night, seeking to minimize the influence of terrain slope on infrared radiation (ACERO; GONZÁLEZ-ASENSIO, 2018; MUTIIBWA; STRACHAN; ALBRIGHT, 2015; ZHANG et al., 2014).

Regarding precipitation (mm), those were collected from the National Water and Basic Sanitation Agency (ANA) “Data Acquisition v1.o (QGIS3)” (PETRY; JARDIM; FAN, 2021). Precipitation data have spatial resolution between 0.25 x 1.0 km and collections have a temporal resolution of 1 day (https://www.gov.br/ana/pt-br). Data collections are carried out through rainfall stations, with the acquisition process being completed from the platform “ANA Data Acquisition”, linked to the Geographic Information System (GIS) software QGIS 3.10.14.

2.3.3. Soil organic carbon stock (SCS)

Estimates of soil organic carbon stock (SCS t/ha – mean 0 - 0.30 m) were obtained from the SoilGrids250m 2.0 platform (https://soilgrids.org/) provides the mapping of different soil attributes around the globe. The values have a spatialization of 0.25 x 1 km, with the composition of planetary images of the ground with about 1.4 billion pixels (POGGIO et al., 2017). SCS values were estimated using machine learning models (random forest, gradient boosting, and multinomial logistic regression) (HENGL et al., 2017), using national and international databases, containing 110,000 soil information collected in the field (COOPER et al., 2005; HENGL et al., 2014; POGGIO et al., 2017).

The accuracy of SoilGrids250m 2.0 estimates ranges from 23 to 51%, depending on the distance between the collection points of information used in regional modeling (HENGL et al., 2014). Therefore, the spatial resolution and its respective reliability vary according to distances from the on-site collection points over the area.

The collection points used by the SoilGrids250m 2.0 platform do not have a uniform distribution. The platform uses published soil property data independent of a systematic ordering of collection points. Thus, the values presented around the spatialization for the present study were collected from the estimated values for SCS t/ha (mean 0 - 0.30 m) (COOPER et al., 2005; HENGL et al., 2014; POGGIO et al., 2017).

2.3.4. Data manipulation and treatment: temporal and descriptive statistics variability

For the spatiotemporal data analysis, descriptive statistical analyzes were used, Pearson ($p < 0.05$), Student t-test ($p < 0.05$), and Linear regression ($p < 0.001$), through Software R version 3.6.2. Graphics were also created using Power BI software. To improve understanding was organed a flowchart to illustrate the methods used until the elaboration of the results (Fig. 4).

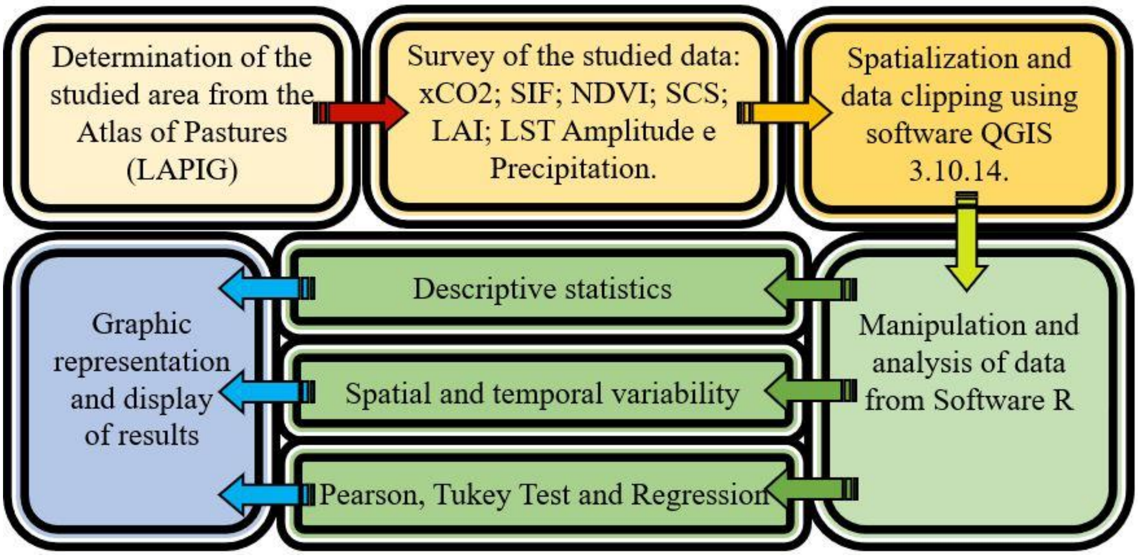

Figure 4. Data treatment and manipulation approach.

Some procedures were necessary to enable the proposed statistical analyses. Data were separated into two groups: the first represents data capable of varying in time and space, as in the case of xCO2, SIF, NDVI, LAI, LST Amplitude, Precipitation. This set of variables is measurable throughout the historical series and specialized in pasture areas, thus characterizing space-time variables.

The second group has the addition of SCS t/ha (mean 0 - 0.30 m), for having only spatial resolution. This is because the data provided by the SoilGrids250m 2.0 platform has no temporal distribution, only spatial. Thus, to enable the desired comparisons between the SCS and the spatiotemporal dataset, unique averages were created for each georeferenced collection point, standardizing them spatially and allowing for comparisons and statistical analysis between them.

The xCO2 was corrected removing its trend linear growth trend along years (ARTURSSON et al., 2000). For all variables studied normality tests, homoscedasticity, and distribution probability were applied. Outliers were also removed using the method of interquartile range (IGR) identification (WANG; CAJA; GÓMEZ, 2018).

2.4. Results

2.4.1. Comparing degraded and managed pastures: xCO2, SCS, vegetative and climatic variables

Figure 5 presents the linear correlation matrix of the studied variables. This was developed from the total dataset, therefore, without distinguishing pasture classes. This approach sought to highlight the correlation between all variables together, in order to demonstrate the strength and behavior interaction of the dataset.

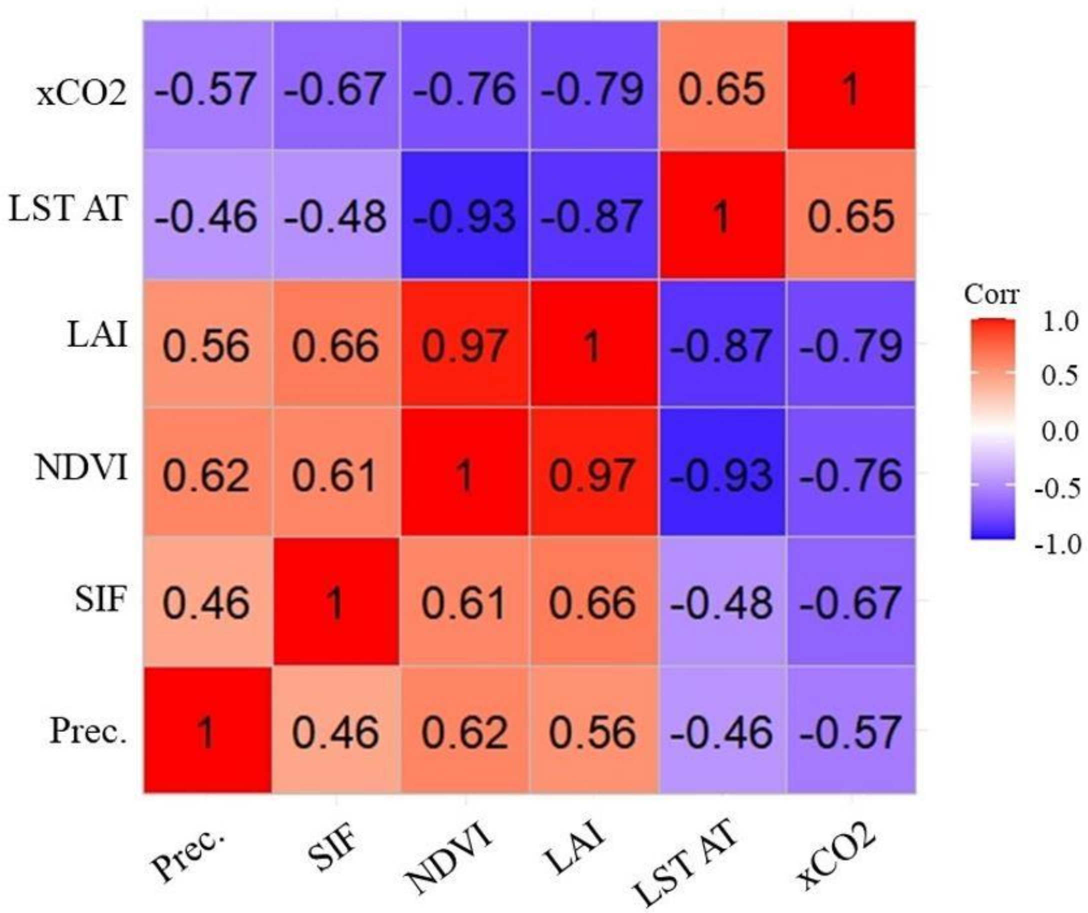

Figure 5. Pearson linear correlation matrix ($p < 0.05$). xCO2 (ppm); LST Amplitude (LST AT); LAI m^2/m^2 (LAI); NDVI; SIF ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$); and Precipitation (mm).

Thus, xCO2 was negatively related to Precipitation (– 0.57), SIF (– 0.67), NDVI (– 0.76), and LAI (– 0.79) ($p<0.05$), as also observed by other authors (DA COSTA et al., 2021; MORAIS FILHO et al., 2021; SIABI; FALAHATKAR; ALAVI, 2019). Differently, xCO2 related positively with LST Amplitude (0.65), which also presented a strong negative correlation with NDVI (– 0.93) and LAI (– 0.87) ($p<0.05$).

Temporal variability and the contrast between degraded x managed adoption of xCO2, vegetative and climatic variables are visualized in Figure 6 (Fig. 6A, C, E, G, I e K) and through Boxplot graphics in conjunction with Student t-test (Fig. 6B, D, F, H and J). In a general way, all variables confirm strong seasonality and major statistical differences when compared degraded (DP) and managed (MP) pasture classes. The seasons directly influence all variables, most of them presenting higher values at rainy periods (October to April) than in the drought period (from May to September).

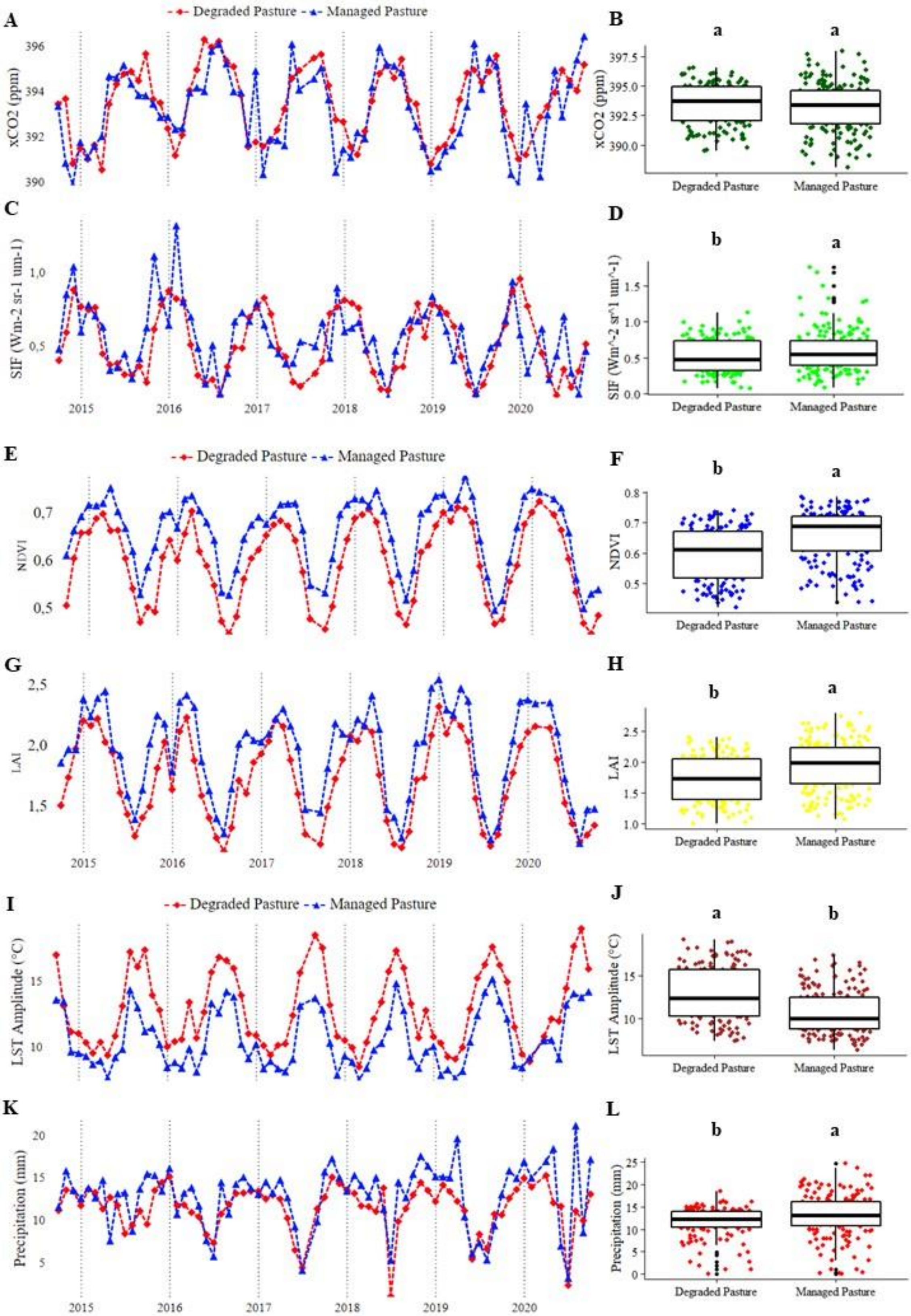

Figure 6. Monthly averages throughout the time series: xCO2 (ppm) (A, B); SIF (W m^{-2} sr^{-1} μm^{-1}) (C, D); NDVI (E, F); LAI (m^2/m^2) (G, H); LST Amplitude (°C) (I, J); and Precipitation (mm) (K, J), for Degraded (DP) and Managed Pastures (MP), where means followed by the same letter do not differ from each other by the Student t-test at a 5% significance level (p<0.05).

xCO_2 presented the mean value of 393.4 ± 0.15 ppm (standard error of mean) over the DP area with a minimum/maximum of 389.5 and 396.6 ppm, respectively. In MP mean of 393.3 ± 0.1 ppm, with a minimum of 388.1 and a maximum of 397.9 ppm were observed, but no significant difference (Student t-test $p > 0.05$) was observed when comparing xCO_2 between pasture classes (Fig. 6B).

For the SIF values, the DP presented were 0.520 ± 0.020 (standard error of mean) with a minimum of 0.072 W m^{-2} $sr^{-1}\mu m^{-1}$ and a maximum of 1,128 W m^{-2} $sr^{-1}\mu m^{-1}$, in drought and rainy seasons, respectively. In MP mean value was higher, 0.60 ± 0.022 W m^{-2} $sr^{-1}\mu m^{-1}$, with a minimum and maximum of 0.081 and 1,762 W m^{-2} $sr^{-1}\mu m^{-1}$, respectively. The highest fluorescence emission from the photosynthetic activity was seen in the MP areas and differed statistically (Student t-test $p < 0.05$) from the DP.

The temporal variability of SIF (W m^{-2} sr^{-1} μm^{-1}), NDVI and LAI (m^2/m^2) (Fig. 6C, E, and G) are inversely related to xCO_2 certainly due to seasonality. This effect was also observed in studies conducted on sugarcane, grassland, and other crops perennial crops (DA COSTA et al., 2021; MORAIS FILHO et al., 2021). All vegetative variables demonstrated significant differences (Student t-test $p<0.05$), showing that the MP has higher values when compared to the DP (Fig. 6D, F, and H) (SIABI; FALAHATKAR; ALAVI, 2019; VALLE JÚNIOR et al., 2019).

Precipitation (mm) for DP had a mean of 11.57 ± 0.30 mm and MP means of 13.01 ± 0.44 mm (Fig. 6K). These differences were expressed by the analysis (Student t-test $p < 0.05$), where DP was shown to have lower values compared to MP (Fig. 6I). The highlights between the classes of pastures are seen in October 2015, April 2019 and August 2020, with average differences of 6.0, 7.5, and 10 mm, respectively.

Still for the hypothesis test (Student t-test $p < 0.05$), significant differences for soil carbon stock (SCS t/ha - mean 0 - 0.30 m) were observed between the classes of pastures ($p < 0.05$), with values superiors under MP. The SCS for the DP presented a mean of 36.0 t ha^{-1} ± 0.32, a minimum of 25.0, and a maximum of 48.0 t ha^{-1}. For MP, mean 41.7 ± 0.65 t/ha, minimum 26.0, and maximum 62.0 t/ha were obtained.

Figure 7 presents the linear regressions ($p < 0.001$) between atmospheric xCO2 and all other variables, distinguishing DP from MP. All analyzes comparing pasture classes presented significance, except for the SCS (t/ha - mean 0 - 0.30 m) over the MP areas (Fig. 7F). The behavior of the straight line in relation to xCO2 (ppm) was negatively related to SIF (W m^{-2} sr^{-1} μm^{-1}), NDVI, LAI (m^2/m^2), and precipitation (mm), however, positively with LST Amplitude (°C) and SCS (t/ha), for both pasture classes. In addition, the SIF, Precipitation, and SCS were different between the pasture classes, from standard error.

Regression between xCO2 and SIF (Fig. 7A) separating DP and MP shows a higher determination coefficient (adjusted R^2) in the negative relationship for DP (R^2 = 0.633) and for MP (R^2 = 0.411). With differences of 0.222 for the R^2 values between pasture classes, the superior relevance of SIF on the behavior of atmospheric xCO2 in DP was observed. The difference between the R^2 values was 0.243 between the classes. The regression analysis for xCO2 and SCS (t/ha – mean 0 - 0.30 m) showed a positive relationship for DP (R^2 = 0.226, p = 0.00018) and MP (R^2 = 0.083, p = 0.3967), however, significance only for DP ($p<0.001$).

xCO2 relates negatively with NDVI and LAI, demonstrating negative and significant pasture class ratios. For this too, superiority of R^2 values was observed for NDVI under DP (R^2 = 0.680, $p<0.001$) compared to MP (R^2 = 0.583, $p<0.001$) (Fig. 5B). With less intensity, the same was observed for the LAI values, where the DP values (R^2 = 0.678, $p<0.001$) were higher than those of MP (R^2 = 0.612, $p<0.001$) (Fig. 7C).

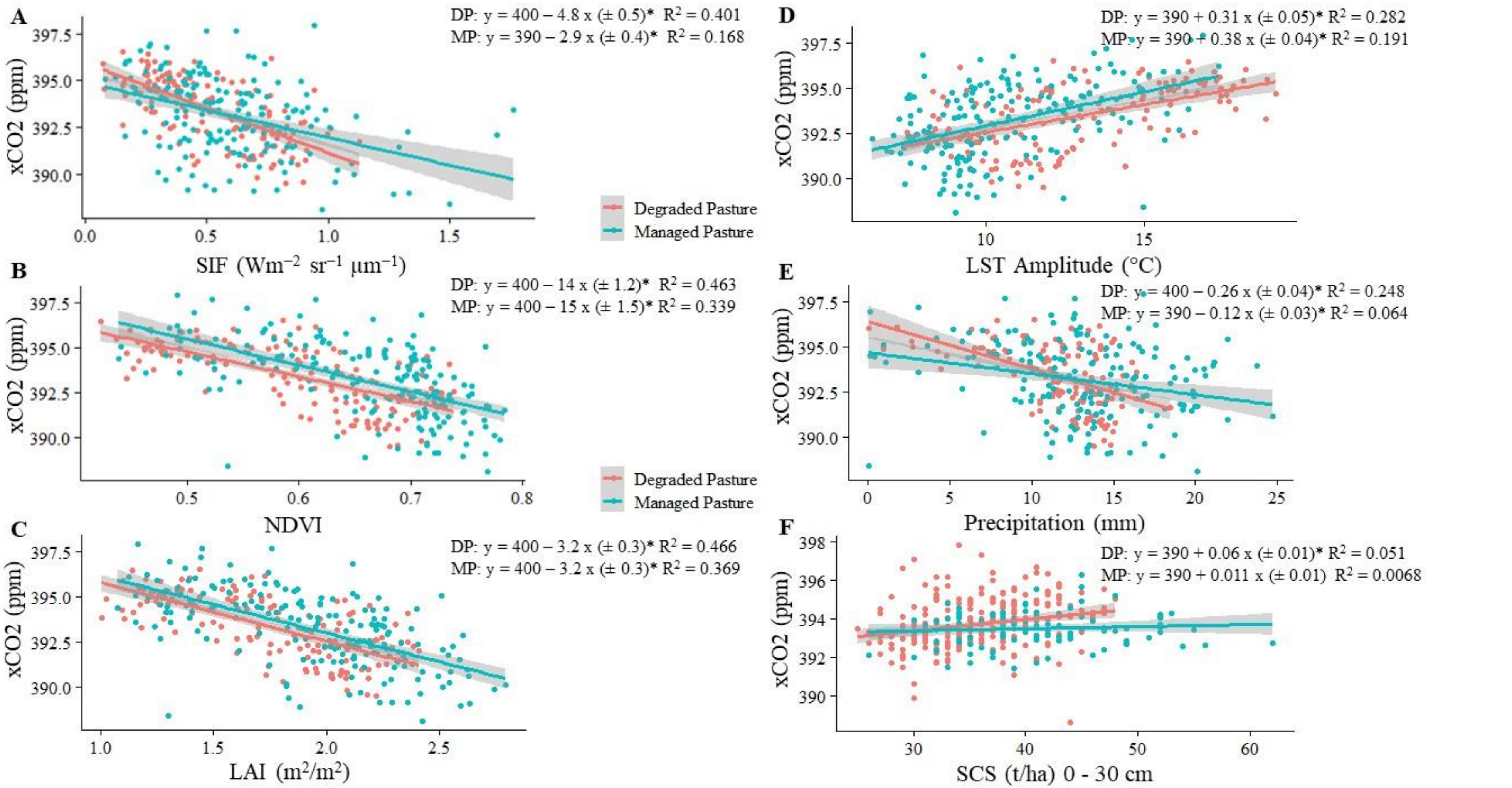

Figure 7. Linear regression for degraded (DP) and managed (MP) pastures, displaying the equation for the pasture classes with the standard error to the angle coefficient, the values of adjusted R^2, and indication for p <0.001 (*). For xCO2 ppm around the SIF W m^{-2} sr^{-1} μm^{-1} (A); NDVI (B); LAI m^2/m^2 (C); LST Amplitude (D); Precipitation mm (E); and SCS t/ha (F).

For the regression between xCO2 and LST Amplitude (Fig. 7D), a positive and significant relationship was observed for DP ($R^2 = 0.531$, $p < 0.001$) and MP ($R^2 = 0.446$, $p < 0.001$). Other important relationships in this study were observed for LST Amplitude between SCS and NDVI. For LST Amplitude and SCS, negative and significant relationships were observed, demonstrated by regression analysis for DP ($R^2 = 0.318$, $p < 0.001$) and MP ($R^2 = 0.191$, $p < 0.05$). For LST Amplitude and NDVI, significant ($p<0.001$) and negative relationships were observed for both classes of pastures, being for the DP $R^2 = 0.900$ and for the MP $R^2 = 0.808$.

2.5. Discussions

2.5.1. Vegetative and climatic variability around xCO2 under degraded and managed pastures

The linear regression and negative correction values between xCO2 and vegetative variables highlight the role of vegetation on atmospheric CO_2 capture, as already demonstrated by Keeling et al. (1976). Similar results were recently found by Sun et al. (2018), da Costa et al. (2021), and Morais Filho et al. (2021), where NDVI and LAI were significantly and negatively related to xCO2 (Fig. 5 and 7). Those relationships are seen as the vegetation working as a sink of atmospheric carbon, as reported by several authors (DA COSTA et al., 2021; HOWE, 2015; KEELING; BACASTOW; BAINBRIDGE, 1976; MORAIS FILHO et al., 2021).

LST Amplitude relates negatively with NDVI and LAI demonstrates that the vegetation cover directly impacts the thermal amplitude (Fig. 5). Da Silva et al., 2018 highlight that ground cover reduced the average soil temperature by approximately 6.4% under Yacon potato, contributing to the soil water storage capacity by 35%. Similar results were found by Acero and González-Asensio (2018), concluding that vegetation over rural areas contributed to the protection of the soil from solar radiation, impacting the maximum and minimum values of the temperature. These considerations explain the higher LST Amplitude values under local DP where lower SIF, NDVI, and LAI values were observed.

The values of LAI and NDVI significantly lower in DP compared to MP contributed to higher temperature amplitude between day and night (ACERO;

GONZÁLEZ-ASENSIO, 2018). The strong correlation between these variables and the differences between pasture classes highlight LST Amplitude as an essential variable that, in addition to others, could be used for pastures classification, as reported in the works of da Silva Quinaia et al. (2021), Parente et al. (2019) and Valle Júnior et al. (2019).

For correlation analysis, precipitation (mm) showed a positive relationship of intermediate strength for the vegetative variables. This result demonstrates that precipitation boosted the vegetative development of pastures, explaining the positive relationship between these variables (XIAODONG et al., 2013; ZHOU et al., 2016). Additionally, the negative relationship of intermediate force for xCO2, demonstrates that precipitation also impacted atmospheric CO_2 (HOWE, 2015; KEELING; BACASTOW; BAINBRIDGE, 1976). The precipitation boosted the vegetation in the vigor, photosynthetic activity, and ground cover of pastures, making them more capable of capturing atmospheric CO_2 and thus explaining the negative relationship between the variables (KENEA et al., 2021; XIAODONG et al., 2013; ZHOU et al., 2016).

For the comparison of pasture classes from Student t-test and linear regression (Fig. 6K, L and 7E), showed that MP received significantly higher amounts of Precipitation over the historical series than DP, even though it has more than twice as much area (58.5%) when compared to MP (Table 1). Therefore, it was observed again that different amounts of rainfall in each class of pasture directly impact the vegetative indices (ZHOU et al., 2016), however, the inverse also becomes true. Since, precipitation on the classes of pastures became more voluminous also by the action of the vegetation (MAKARIEVA; GORSHKOV, 2007; NAGLER et al., 2007; VICENTINI et al., 2019; ZEMP et al., 2017; ZHOU et al., 2016).

For Makarieva and Gorshkov (2007) the physical principles involving precipitation demonstrate that moist air from areas with weak evapotranspiration moves to areas with stronger evapotranspiration. According to the authors, the vapor pressure of areas with strong evapotranspiration, as it moves through the atmospheric column, creates a low-pressure zone (MAKARIEVA; GORSHKOV, 2007; NAGLER et al., 2007; SHEIL; MURDIYARSO, 2009). Seeking to reestablish the balance between atmospheric forcings, the weak evapotranspiration zones supply the strongest evapotranspiration zones (MAKARIEVA; GORSHKOV, 2007; SHEIL; MURDIYARSO, 2009). Thus, this atmospheric physic chemical mechanism produces the cyclical retro-supply of precipitation, creating a system called “feedbacks” (MAKARIEVA; GORSHKOV, 2007; SHEIL; MURDIYARSO, 2009; WOODALL et al., 2012).

These observations are mainly associated with tropical rainforests (CHAMBERS; ARTAXO, 2017; LEITE-FILHO et al., 2021; SHEIL; MURDIYARSO, 2009; XIAODONG et al., 2013; ZEMP et al., 2017). The evapotranspiration of this type of vegetation is related to the high leaf area index, root depth, as well as the length, roughness, and reflectivity of the forest canopy (SHEIL; MURDIYARSO, 2009; WOODALL et al., 2012). Aspects capable of sustaining the upward displacement of air and attracting moist air from the ocean, thus modifying the dynamics of local precipitation (CHAMBERS; ARTAXO, 2017; LEITE-FILHO et al., 2021; MAKARIEVA; GORSHKOV, 2007; SHEIL; MURDIYARSO, 2009; WOODALL et al., 2012; ZEMP et al., 2017).

The positive relationship between vegetation indices, evapotranspiration, and precipitation was observed by other authors when comparing pastures and shrub vegetation in other countries (ZHOU et al., 2016) and between the Brazilian Cerrado and Amazonia biome (COSTA; PIRES, 2010). Therefore, taking as a basis Makarieva and Gorshkov (2007), the vegetative values under MP produced by agricultural management, impacts evapotranspiration and formation of moist air masses over the area altering the frequency of precipitation (COSTA; PIRES, 2010; NAGLER et al., 2007; SHEIL; MURDIYARSO, 2009; ZEMP et al., 2017). Thus, the mechanisms developed by Makarieva and Gorshkov (2007) are important tools to explain the differences in precipitation between DP and MP, mainly through the contrasts of NDVI, LAI, SCS, and LST Amplitude.

In line with the positive impact of agricultural management and the “feedback” effect of precipitation on MP, the results observed in the linear regression between precipitation and xCO2 (Fig. 7E) highlight rainfall as an important regulator of atmospheric CO_2. As the rains replenish the vegetation, these become more capable of capturing CO_2 through photosynthesis, fixing it in physiological structures, and later storing it in soil compartments. Such statements are confirmed when observing the values of SCS (t/ha – mean 0 - 0.30 m) for the classes of pastures, where the MP presented statistical superiority for this variable in relation to the DP.

Besides the vegetative impact on xCO2 discussed earlier, Moitinho et al. (2015) and Vincentini et al. (2019) demonstrated that the microbiological activity responsible for the metabolization of soil carbon and the consequent production of CO_2 is driven by rainfall and moisture content, thus explaining the higher R^2 under DP. Thus, recovering degraded pasture areas in central Brazil is important to supply a beneficial agroecosystem and environmental cyclical system.

Therefore, pasture management becomes a fundamental tool as nature-basic solutions, mainly based on two principles: (i) on a large scale, areas with better vegetative values generated by good management conditions produce higher rainfall (feedback effect); and consequently, (ii) rainfall amounts and frequencies impact the vegetative capacity of pastures to remove and store the CO_2 available in the atmosphere.

2.5.2. Interaction between Soil Carbon Stocks, Vegetative and Climate Aspects around xCO2

The positive linear relationship between xCO2 and SCS indicates a possible source of soil carbon by oxidation and subsequent CO_2 emission to the atmosphere, especially in DP areas (Fig 5 E). Other authors have shown that soil carbon has a positive relationship with CO_2 flux, which is quite significant and comparable to photosynthetic capture (ABDALLA et al., 2018; BRAZ et al., 2013; FIGUEIREDO et al., 2017; TAVANTI et al., 2020).

The significant relation between xCO2 and SCS observed only in DP demonstrates that soil organic carbon does not significantly influence atmospheric CO_2 over MP areas. The increase in soil organic carbon as related to a sustainable agricultural practice (TAVANTI et al., 2020) contributes to stabilizing soil carbon resulting in higher values of SCS in MP when compared to DP (ABDALLA et al., 2018; ALVARES et al., 2013; CHAPLOT; COOPER, 2015; FIGUEIREDO et al., 2017).

Not observed for DP, authors such as Abdalla et al. (2018) and Figueiredo et al. (2017), demonstrate that in the soil CO_2 flux, they are 41 and 15% higher in pastures with intermediate degradation and highly degradation, respectively. Furthermore, Abdalla et al. (2018) and Figueiredo et al. (2017) demonstrate that soil carbon from undegraded pastures, of intermediate degradation and highly degraded present, respectively, low, high, and intermediate average emission of CO_2. Essential results for what was observed under the MP, because, as visualized by Abdalla et al. (2018), were the xCO2 contents of the DP those most impacted by the carbon content stored in the soil (FIGUEIREDO et al., 2017).

Chaplot and Cooper (2015) demonstrate that in pastures with intermediate degradation, in addition to higher SCS levels compared to highly degraded ones, these generally have carbon at higher levels of instability and exposure when compared to non-degraded pastures. Thus, authors like Chaplot and Cooper (2015) and Abdalla et al. (2018), highlights that these are the main factors that contribute to the flux of CO_2 to the atmosphere in pastures with different levels of degradation (ABDALLA et al., 2018; CHAPLOT; COOPER, 2015; FIGUEIREDO et al., 2017).

Like SCS, agricultural management also directly impacts vegetative attributes on pastures (ACERO; GONZÁLEZ-ASENSIO, 2018; YOUNESZADEH; AMIRI; PILESJO, 2015). Similar results were observed by Abdalla et al. (2018), where positive relationships between soil carbon content and aboveground pasture biomass were significantly higher in non-degraded pastures and lower in highly degraded pastures, similar to what was observed in the present study (ABDALLA et al., 2018; FIGUEIREDO et al., 2017).

Positive values between xCO2 and LST Amplitude were observed for linear regression and correlation. Despite being positively correlated with xCO2, the LST Amplitude and SCS variables showed negative relationships with each other. These results indicate that higher SCS values are related to lower LST Amplitude values (ABDALLA et al., 2018; CHAPLOT; COOPER, 2015). Abdalla et al. (2018) and Zuh et al. (2019) reported that SCS impacts soil surface temperature. This is because soils with higher organic carbon contents have lower thermal diffusivity (ZHU et al., 2019). Therefore, the higher LST Amplitude values in the DP areas (Fig. 5) result from the low SCS contents (ZHU et al., 2019).

For Student t-test, LST Amplitude and SCS showed significant differences for pasture classes. However, LST Amplitude was higher in DP and lower in MP, but the opposite was observed for SCS, higher in MP and lower in DP. However, the negative relationship between LST Amplitude and SCS also indicates that the temperature above the ground contributes to lower SCS values. Cheng et al. (2021) and da Silva et al. (2018), demonstrate that soil carbon stability is directly affected by temperature. This effect is explained by the action of temperature on carbon protection and by microbiological activity, impacting mainly on the first centimeters of the ground (CHENG et al., 2021; DA SILVA et al., 2018).

Results similar to those found by Cheng et al. (2021), are visualized in the time series for LST Amplitude (Fig. 4I), mainly during winter, where values under DP stand out from the MP. According to Cheng et al. (2021), the rapid warming of the Tundra soil in winter corresponds to higher carbon degradation rates by fungal communities, which are thus related to higher CO_2 fluxes.

Thus, it is possible to state that LST Amplitude is a result of SCS values because the carbon in the soil allows for slower thermal exchanges (ZHU et al., 2019). However, the SCS values are results of the LST Amplitude, mainly because rapid soil warming during winter results in carbon instability and increased microbiological activities, responsible for greater carbon fluxes to the atmosphere and lower levels in the soil. Therefore, explaining the consequent positive relationships of xCO2 between SCS and LST Amplitude and the results observed on the DP.

Similar results were found by Acero and González-Asensio (2018), wherein in the summer, the development of vegetation delayed the temperature gain of the soil surface during the morning, impacting the temperature throughout the day. This aspect explains the values of LST Amplitude over DP being more prominent when compared to MP, especially during winter (ACERO; GONZÁLEZ-ASENSIO, 2018).

Thus, therefore, it can be highlighted that the main contributions of CO_2 are produced by degraded pastures that still have carbon in the soil, for severely impacting particulate organic matter stored in the most labile fractions in the soil and for not having a significant vegetative capacity to capture CO_2 from the atmosphere (ABDALLA et al., 2018; CHAPLOT; COOPER, 2015; FIGUEIREDO et al., 2017; KEELING; BACASTOW; BAINBRIDGE, 1976). According to the LAPIG platform (PARENTE et al., 2019), Brazil has 65 million hectares of pasture classified as the intermediate intensity of degradation, 38.76% of the total, and 53.9 million hectares with the severe intensity of degradation, 32.14% of the total.

Thus, it can be noted that these areas, especially those classified with intermediate degradation, if not recovered, they lost their carbon stocks to the atmosphere in the form of CO_2 (ABDALLA et al., 2018; FIGUEIREDO et al., 2017; TAVANTI et al., 2020). It is worth noting that it is against effects like these that research on greenhouse gases and soil carbon is carried out. Exactly to prevent soil carbon from being emitted into the atmosphere, thus aggravating a series of facts involving global climate change (BOSSIO et al., 2020).

2.6. Conclusions

The managed pastures presented higher values for SCS (t/ha – mean 0 - 0.30 m), SIF ($W\ m^{-2}\ sr^{-1}\ \mu m^{-1}$), NDVI, LAI ($m^2/m^2$) and Precipitation when compared to degraded pastures. In addition, the time variability of xCO2 and its negative relationship with SIF, NDVI, LAI, Precipitation and positive properties for SCS and LST Amplitude (°C), indicate that these are control factors in the capture, and source of atmospheric CO_2, respectively.

The LST Amplitude between night and day significantly correlated with SCS and xCO2, inverse and directly proportional, respectively. This result showed that LST Amplitude could act as a new indicator of atmospheric CO_2 dynamics and characterization of degradation of degraded pastures.

The managed pastures showed significant superiority in rainfall volume when compared to degraded pasture. This result highlights that the vegetative indices under managed pastures were able to act in modifying the amount of local rainfall. Concluding, therefore, that the agricultural management of pastures supplies a system of good vegetation and greater amounts of rain, directly impacting the capacity of the areas to sequester atmospheric CO_2.

This study also pointed out that those degraded pasture with lower soil carbon could be a source of CO_2 for the atmosphere compared to managed pastures. Linear regression analysis showed that all the studied variables are better related to CO_2 atmospheric concentration in degraded pasture, mainly in SIF, precipitation, and SCS. The low vegetative indices observed under the degraded pasture contributed to higher LST Amplitude which is negatively associated with SCS.

Therefore, these results demonstrate that converting degraded to managed pastures could help mitigate atmospheric CO_2 by soil and above biomass incorporation, and possibly helping also in some others agrosystem services such as increasing yield and reducing regional temperatures. These findings may favor nature-based solutions mainly carbon sequestration actions, a fundamental part of programs on a national scale (Low Carbon Emission Agriculture Program - ABC Program and Nationally Determined Contributions - NDC do Brazil) with goals for the recovery of 30 million hectares of degraded pasture, and global scale (regulated and voluntary carbon credit market).

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CHAPTER 3 – FINAL REMARKS

3.1. Future Perspectives

Remote sensing comparisons between degraded and managed pastures were important to characterize their contrasts. Such comparisons demonstrated that some of the variables can be studied to better understand their potential. As an example, the variables LST Amplitude and Precipitation.

The LST Amplitude showed the potential to discriminate the two classes of pastures studied in the present study, as well as the ability to impact higher atmospheric concentrations of CO_2 and instability in soil organic carbon. Studies involving this variable together with air temperature and soil carbon stock levels studied In Loco may offer more accurate contributions to its potential.

Precipitation showed higher levels on managed pastures. This result can be supplemented with other variables for better understanding. Comparisons between pasture classes and Precipitation could be complemented with: Potential Evapotranspiration, Albedo, Rugosity, and Soil Moisture Active Passive (SMAP). These variables would help the understanding of some of the possible movements of humid air mass that occur over the pastures.

Other greenhouse gas (GHG) would also be an alternative to enrich the study, for example Methane (CH_4). There are some published articles involving CH_4 and pastures, however, no studies were observed that included degraded pastures and managed this variable. A difficulty in this sense would be the spatialization of the satellite data collection points. Therefore, it would be necessary to use geostatistical tools, such as Kriging, to make this comparison possible.

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