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**UNIVERSIDADE ESTADUAL PAULISTA – UNESP
CÂMPUS DE JABOTICABAL**

**BOTTOM-UP AND TOP-DOWN METHODS FOR
ESTIMATIONS OF GREENHOUSE GASES SOURCES AND
SINKS**

**Luis Miguel da Costa
Engenheiro Agrônomo**

**UNIVERSIDADE ESTADUAL PAULISTA – UNESP
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ESTIMATIONS OF GREENHOUSE GASES SOURCES AND
SINKS**

Luis Miguel da Costa

Orientador: Prof. Dr. Newton La Scala Jr.

Coorientadores: Prof. Dr. Alan Rodrigo Panosso

Coorientadores: Prof. Dr. Roberto Colombo

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AUTOR: LUIS MIGUEL DA COSTA

ORIENTADOR: NEWTON LA SCALA JUNIOR

COORIENTADOR: ALAN RODRIGO PANOSSO

COORIENTADOR: ROBERTO COLOMBO

Aprovado como parte das exigências para obtenção do Título de Mestre em Agronomia (Produção Vegetal), pela Comissão Examinadora:

Prof. Dr. NEWTON LA SCALA JUNIOR (Participação Virtual)
Departamento de Ciências Exatas / FCAV UNESP Jaboticabal



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Pesquisador Dr. CELSO HENRIQUE LEITE SILVA JUNIOR (Participação Virtual)
Instituto de Pesquisa Ambiental da Amazônia (IPAM) / Brasília/DF



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Prof. Dr. GLAUCO DE SOUZA ROLIM (Participação Virtual)
Departamento de Ciências Exatas / FCAV UNESP Jaboticabal

Jaboticabal, 16 de setembro de 2025

DADOS CURRICULARES DO AUTOR

LUIS MIGUEL DA COSTA – nascido em 15 de fevereiro de 2000 no município de Araraquara – São Paulo. Engenheiro Agrônomo pela Universidade Estadual Paulista “Júlio de Mesquita Filho”, Faculdade de Ciências Agrárias e Veterinárias, campus de Jaboticabal. Iniciou em 2024 o Mestrado junto ao Programa de Pós-Graduação em Agronomia (Produção Vegetal) na Universidade Estadual Paulista “Júlio de Mesquita Filho”, Faculdade de Ciências Agrárias e Veterinárias, campus de Jaboticabal. Atua desde 2020 no entendimento da dinâmica do CO₂ atmosférico e seus fatores de controle e em sensoriamento remoto do meio ambiente, com recentes contribuições em análises multicritério para definição de áreas prioritárias para pagamento por serviços ambientais. É membro dos grupos de pesquisa: Emissão de CO₂ do solo e balanço de gases de efeito estufa em sistemas agrícolas; Grupo de Estudos em Estatística Computacional Aplicada (GEECA), *Remote Sensing of Environmental Dynamics Laboratory* (LTDA/UNIMIB) e na Fundação Getúlio Vargas (FGVAgro) onde desenvolve projetos no âmbito de: Sensoriamento Remoto; Data Science; Concentração atmosférica de CO₂ e seus fatores de controle; Fluorescência da Clorofila Induzida pelo Sol e Temperatura da Superfície.

*“Do not quench your inspiration and your imagination;
do not become the slave of your model.”*

Vicent Van Gogh

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BOTTOM-UP AND TOP-DOWN METHODS FOR ESTIMATIONS OF GREENHOUSE GASES SOURCES AND SINKS

Resumo – As emissões de gases com efeito de estufa (GEE) são a principal causa das alterações climáticas, pelo que a sua monitorização é essencial para estabelecer políticas de mitigação à escala local e global. Nas últimas décadas, o número de estudos publicados sobre as potenciais fontes e sumidouros de GEE tem aumentado exponencialmente. Apesar disso, a identificação de fontes pontuais continua a ser um desafio devido à falta de dados ou à incerteza atmosférica. Além disso, em comparação com o número de estudos dedicados a lidar com as fontes de GEE, menos estudos têm sido realizados em relação à identificação da remoção de GEE, principalmente devido à absorção de CO₂ através da fotossíntese. Neste trabalho exploramos a identificação de não somente fontes, mas também remoções de GEE no Brasil usando duas abordagens. Na primeira abordagem, comparamos dois inventários GEE (*bottom up*), sendo um tradicional e outro com uma abordagem que combina dados de sensoriamento remoto, modelos de aprendizado de máquina e diretrizes do IPCC para relatar fontes e emissões pontuais em nível global. Na segunda abordagem (*top-down*), propomos uma estrutura simples baseada em dados do Orbiting Carbon Observatory-2 (OCO-2) para detectar fontes e sumidouros de CO₂ no território brasileiro. Apesar das diferenças entre as abordagens, principalmente na intensidade, ambas apontam que as regiões com maior frequência de sumidouros estão localizadas na Caatinga e no domínio mais profundo da Amazônia; enquanto que as regiões com maior frequência de fontes estão localizadas na transição entre os biomas Cerrado e Amazônia. A Mudança no Uso e Cobertura do Solo (LULCC) e atividades como o uso do fogo também apontam que essa região está sofrendo com a ação antrópica. Por outro lado, os dados de Fluorescência de Clorofila Solar Induzida (SIF) apontam que a atividade fotossintética no domínio da Caatinga está aumentando ao longo dos últimos anos. Portanto, apesar das incertezas relacionadas a ambas as abordagens, elas concordam na identificação de fontes e sumidouros; no entanto, discordam na quantidade estimada, principalmente devido à diferença metodológica, fundamentalmente baseadas em bottom-up (inventários) and top-down (a partir da concentração atmosférica).

Palavras-chave: Mudanças Climáticas, Fontes de CO₂; Remoção de CO₂; Sensoriamento Remoto; Inventário de GEE

BOTTOM-UP AND TOP-DOWN METHODS FOR ESTIMATIONS OF GREENHOUSE GASES SOURCES AND SINKS

Abstract – Greenhouse gas (GHG) emissions are the main cause of climate change; therefore, its monitoring is essential to establish mitigation policies from local to global scale. Over the last decades, the number of studies published about GHG emissions and removals are exponentially increasing. Despite that, the identification of point sources is still a challenge due to data lack or atmospheric uncertainty. Moreover, compared to number of studies dedicated to deal with GHG sources, fewer studies have been conducted regarding the GHG removal identification, mainly due to CO₂ absorption through photosynthesis. In this work, we explore the identification not only of GHG sources, but also GHG removals in Brazil using two approaches. In the first one we compared a traditional GHG inventory with a new one that combines remote sensing data, machine learning models and IPCC guidelines to report point source and emission at global level. The second approach, we propose a simple framework based on Orbiting Carbon Observatory-2 (OCO-2) data to detect CO₂ source and sinks in the Brazilian territory. Despite the differences between the approaches, mainly in the intensity, both point out that the regions with more sink frequency is located at Caatinga and deepest Amazon domain; meanwhile, the regions with more source frequency is located at the transition between Cerrado and Amazon biomes. Land use and Land Cover Change (LULCC) and activities such as Fire Scar also point out that this region is suffering from anthropogenic action. In the other hand, Solar Induced chlorophyll Fluorescence data point out that Caatinga domain photosynthetic activity is increasing. Therefore, despite the uncertainties related with both approaches, two distinguish methods agrees in the source and sink identification; however, they disagree in the estimated quantity, mainly due methodological difference as the first one is a bottom-up approach meanwhile the other one is a top-down one.

Keywords: Climate Change, CO₂ source; CO₂ removal; Remote sensing; GHG inventory

CHAPTER 1 – General Considerations

1.1 Introduction

The greenhouse effect is a natural process that essentially involves the retention of part of the electromagnetic radiation energy (in the infrared region) emitted by the Sun by molecules such as carbon dioxide (CO₂), water vapor (H₂O), methane (CH₄), nitrogen dioxide (NO₂), ozone (O₃), and other gases. Throughout geological eras, changes in atmospheric composition have led to various climate changes, such as the current global average temperature of 15 °C, which has favored the establishment of life on Earth (Ahrens & Henson, 2012). However, due to human activity, we are enriching the atmosphere with greenhouse gases (GHGs) at rates unseen in the past two million years, leading to an enhanced greenhouse effect, and as a result, our climate is changing rapidly (IPCC, 2021).

These climate changes (driven during the Anthropocene) represent one of the greatest challenges facing society today, with one of their main causes being GHG emissions, especially carbon dioxide (CO₂). CO₂ reached an atmospheric concentration of approximately 428 ppm in 2025 (NOAA, 2024), a 150% increase compared to pre-industrial levels (WMO, 2022). This rise is closely linked to fossil fuel combustion and land-use and land-cover change (LUC). According to the Global Carbon Budget (Friedlingstein, Jones, et al., 2022), 35 gigatons (Gt) of CO₂ equivalent per year were emitted from fossil fuels and approximately 4.4 Gt CO₂ eq per year from land-use and land-cover changes between 2011 and 2021 (Figure 1).

The global carbon cycle

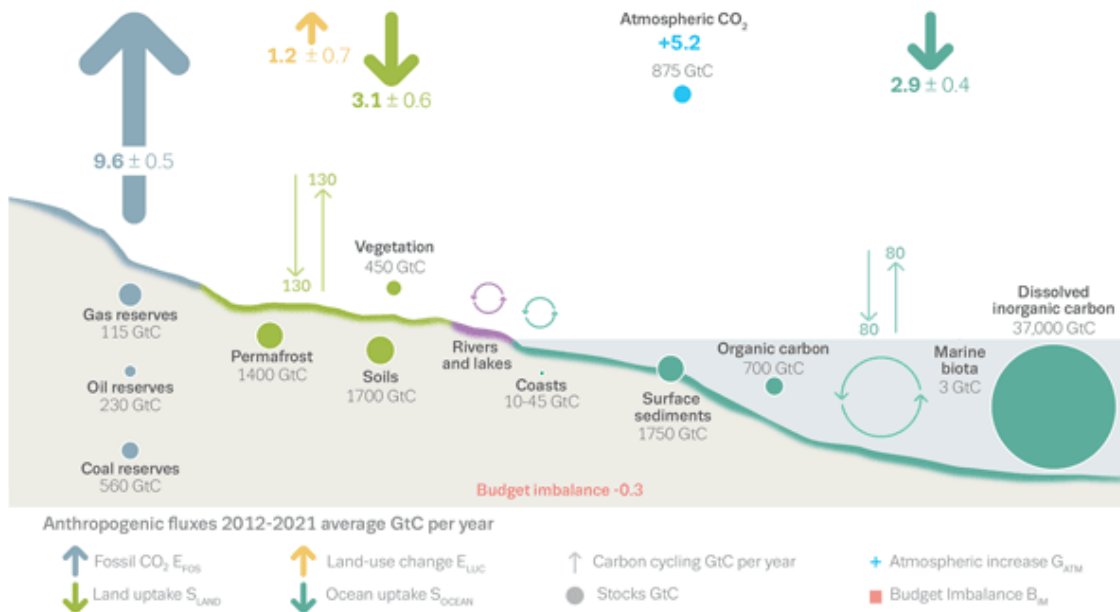


Figure 1. Global Carbon Budget between 2012 – 2022. Source: Friedlingstein et al. (2022)

Although global emissions are primarily related to fossil fuel combustion, Brazil has a distinct emissions profile more closely linked to agricultural activities and land-use and land-cover change, especially deforestation (De Azevedo et al., 2018a). Recently, da Costa et al. (2025) reported that Brazil's net emissions ranged from 0.43 to 2.92 Gt CO₂, depending on the inventory database and the year analyzed. The sectors that contributed the most to emissions were agriculture and land-use and land-cover change. Recently, record levels of deforestation and wildfires have been reported across several Brazilian biomes. Moreover, many fires occurred in places where no fires had ever been recorded since monitoring began (Ferreira Barbosa et al., 2022a; Silveira et al., 2022). However, if both legal and illegal deforestation were halted, the photosynthetic potential of Brazilian biomes could enable the country to achieve net-zero emissions (da Costa, Davitt, et al., 2025; Soterroni et al., 2023a).

Nonetheless, agriculture can play a fundamental role in mitigating CO₂ emissions by sequestering carbon from the atmosphere and storing it in the soil, provided that appropriate practices and management strategies are adopted.

Agricultural practices that reduce the intensity and frequency of soil disturbance, for instance, have been used as a potential mitigation strategy for these gases (Lal & Kimble, 1997; Sharma et al., 2014). Furthermore, according to SEEG estimates (2024), Brazil has the potential to mitigate more than 1,000 million tons of CO₂ equivalent through the restoration of degraded pastures and the implementation of more sustainable systems.

Given the vastness of Brazilian territory, the use of remote sensing for monitoring its natural resources and associated processes is a strategic approach. Several missions have been planned to monitor atmospheric CO₂ (K. Hu et al., 2024). However, despite the extensive satellite network, the identification of localized sources and sinks remains a challenge for the scientific community. In this context, the objective of this dissertation is to explore methodologies for identifying CO₂ sources and sinks, their respective fluxes, and some influencing factors in this dynamic, such as photosynthesis, land-use and land-cover change, fire, and precipitation.

Recently, Lamb et al. (2024) highlighted that GHG removals are not accurately estimated and, in some cases, not even reported. This directly affects the commitments made by countries to mitigate climate change. da Costa et al. (2025) recently demonstrated the impact of different approaches for measuring GHG removals in Brazil, which can lead to differences of up to 1 Gt CO₂-eq. Therefore, it is necessary to understand the greenhouse gas balance and its components independently, comparing different data sources and checking their consistency.

This dissertation is divided into chapters, each organized as a scientific article containing theoretical background, hypothesis, materials and methods, results, discussion, and conclusion. At the end of the dissertation, a Final Considerations section addresses all chapters collectively.

In Chapter 2, we conducted a critical analysis of two greenhouse gas inventories—Climate TRACE and SEEG—and explored how precipitation and photosynthesis influence their estimates to assess how well these inventories capture seasonal variability. Climate TRACE is an inventory that identifies CO₂ sources and removals at fine spatial scales. Using its data, we aggregated emissions into a 0.5° grid to identify sources and sinks over the years. The comparison between inventories

was performed using sectoral net emissions, regression, and correlation analyses at both biome and pixel levels, considering environmental factors.

In Chapter 3, we propose a simple model based on data from the Orbiting Carbon Observatory-2 (OCO-2) to detect CO₂ sources and sinks across Brazil. This approach is based on the hypothesis that CO₂ concentration can be modeled by a simple linear regression over time, and that the rate of increase or decrease can be used to identify sources and sinks. Additionally, we explore the possibility of using this rate to estimate CO₂ fluxes while disregarding atmospheric transport.

3.6 Conclusion

Overall, the CO₂ concentration is rising across the years, with some years with increasing rates beyond 3 ppm. Despite that, there is a spatiotemporal variability in point sources and sinks within the country. We've found that CO₂ sources are more frequently observed in the Cerrado-Amazon transition; meanwhile, CO₂ sinks are more often in the Caatinga and Amazon domains. This is consistent with the deforestation and fire pressure that the transition between those two biomes is suffering. In Caatinga, an increase in photosynthetic activity has been reported for the same period, which explains the frequency of sinks found there. Additionally, despite the limited information of Amazon due to cloud cover, the more internal part of Amazon is less anthropized.

The FCO₂ is a complex process that depends on several factors. The framework proposed here aimed to simplify a first approximation to this phenomenon, combining a linear regression's slope with a known equation. The flux estimated here varied between -22.22 to 23.75 g CO₂ m⁻² month⁻¹. Our results showed, on average, some similarities and discrepancies with the literature, which is probably due to the employed method's uncertainty. The framework used here does not account for atmospheric transport inversion and other traditional modelling aspects, which introduces larger uncertainty in our findings. Moreover, spatial variability shows larger differences between our approach compared with modelling studies. This outcome raises the possibility that the employed method is not capturing the CO₂ flux, but its change instead. Future work needs to test with different modeled data if the proposed approach is capturing the change in flux instead of the actual flux.

Despite the limitations of this work, we believe that at least the identification of sources and sinks is possible using the linear regression slope. Concerning the flux estimation, our findings need further investigations, however, the proposed framework can be a first step towards a quick and easier manner to address flux estimation within a country or region. Furthermore, the inclusion of temperature and pressure data could enhance the quality of the estimation and perhaps be used as a first guess for inversion studies as well.

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