A Better Understanding of CO2 Fluxes within Canadian Boreal Forests through Satellite-Based XCO2 Data

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Abstract

This research seeks a better understanding of carbon fluxes in the Canadian boreal forest in recent years due to the profound impacts of climate change and recent increases in wildfire occurrences. These forests play a significant role in the global carbon cycle, acting as major carbon sinks by absorbing carbon dioxide from the atmosphere. However, the balance between carbon absorption and release is delicate and can be easily disrupted by climate change, leading to increased temperatures, changes in precipitation patterns, and more frequent and severe wildfires. These environmental changes have direct consequences on the carbon balance of the boreal forests. Wildfires, not only release large amounts of stored carbon back into the atmosphere but also alter the forest landscape, affecting its future ability to store carbon.

Canadian boreal forests are significant carbon reservoirs, with approximately 28 pg of carbon across biomass, dead organic matter, and soil. This includes both aboveground biomass and belowground components like roots and soil organic matter. The dynamics of these pools are subject to growth rates, mortality, and disturbances such as fires and insect infestations. This research focuses on quantifying the levels and fluxes of carbon dioxide within Canada's boreal forests.

Fig.1
Adapted from Natural Resources and Environment Canada

With integrating top-down satellite observations with bottom-up field measurements, the research seeks to provide a comprehensive quantification and modeling of CO2 fluxes, enhancing our understanding of carbon sequestration mechanisms. Key objectives include identifying the primary drivers of CO2 exchange variability, assessing the impact of wildfires on forest carbon balances, and assess post-fire forest recovery and its implications for carbon sequestration. Methodologically, the research leverages an array of satellite data, including bias-corrected XCO2 values from OCO-2/3 Lite File, Solar-Induced Fluorescence data, and vegetation indices such as NDVI from MODIS and Landsat satellites. These space-based observations will be coupled with in-situ measurements from networks like FluxNet for validation.
An inverse modeling approach using the Global Earth-system Monitoring model (GEOS-Chem) will assist in interpreting the data to identify the CO2 fluxes and their association with vegetation dynamics and climate conditions.

Furthermore, the study will utilize satellite imagery to analyze land cover changes, fire disturbances, and post-fire regeneration. The research aims to combine top-down satellite observations with bottom-up ground measurements to address the frequency, extent, and intensity of wildfires and their subsequent effect on the forest carbon balance. Furthermore, the study will utilize satellite imagery to analyze land cover changes, fire disturbances, and post-fire regeneration. The research aims to combine top-down satellite observations with bottom-up ground measurements to address the frequency, extent, and intensity of wildfires and their subsequent effect on the forest carbon balance.

Methodology

Satellite Data (OCO-2/3 Lite File, Solar-Induced Fluorescence, NDVI from MODIS and Landsat):

- Utilization of OCO-2 Data for XCO_2 Measurements
The approach to measure CO_2 fluxes in this study is based on XCO_2 data, representing the column-averaged concentrations of carbon dioxide. These data are sourced from the Orbiting Carbon Observatory-2 (OCO-2) satellite, global measurements of atmospheric CO_2 with a spatial resolution of 1.29 square kilometers (2.25 km x 0.70 km footprint). Its orbit allows it to revisit any point on the Earth's surface approximately every 16 days at the equator under nominal operation conditions. However, due to its orbit and operational modes, the actual temporal resolution for a specific location can vary.
The satellite employs spectrometers to measure the intensity of sunlight reflected by the Earth's surface and absorbed by CO_2 molecules, facilitating the calculation of CO_2 concentrations across different atmospheric columns. It employs three high-resolution spectrometers to measure the molecular absorption of sunlight by CO_2 and molecular oxygen (O_2) across three specific bands of the electromagnetic spectrum. These spectrometers are tuned to the near-infrared region where CO_2 and O_2 have strong absorption lines.

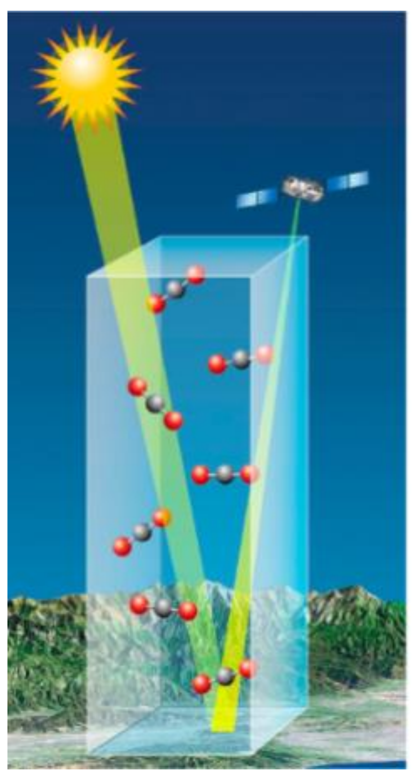

Fig.2
Adapted from NASA Applied Remote Sensing Program, 2023.

- Incorporation of NDVI Data from MODIS
The methodology also incorporates the Normalized Difference Vegetation Index (NDVI) data obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra and Aqua satellites. MODIS provides NDVI data with a spatial resolution of up to 250 meters, enabling detailed monitoring of vegetation health and biomass across the boreal forests. This research utilizes NDVI to identify areas of active photosynthesis and to assess the health and density of forest vegetation, which are critical for understanding the forests' role in carbon absorption and sequestration.

- Application of Solar-Induced Fluorescence (SIF) Data
Additionally, this study employs Solar-Induced Fluorescence (SIF) data to evaluate the photosynthetic activity of the boreal forests. SIF data are extracted from observations made by the OCO-2 satellite, complementing its CO_2 measurements. SIF serves as a proxy for photosynthetic efficiency and plant productivity, reflecting the amount of light energy converted into chemical energy during photosynthesis. By analyzing SIF data, the research aims to quantify the photosynthetic capacity of the boreal forests and to understand how this capacity influences their ability to act as carbon sinks.

In-Situ Measurements (FluxNet):

Ground-based measurements from FluxNet stations are integrated to validate and complement satellite observations. These measurements offer precise data on CO2 fluxes at specific locations, enabling a detailed examination of carbon exchange processes at the microscale. This helps in understanding how local factors influence carbon dynamics, providing a ground truth for satellite data.

Inverse Modeling (Global Earth-system Monitoring Model):

The inverse modeling approach is applied to interpret the combined satellite and in-situ data, aiming to identify specific CO2 fluxes and their association with various environmental factors. This modeling helps in deducing the net carbon exchange rates, distinguishing between sources and sinks of carbon within the boreal forests. It's particularly valuable for analyzing how vegetation dynamics and climate conditions affect carbon fluxes.

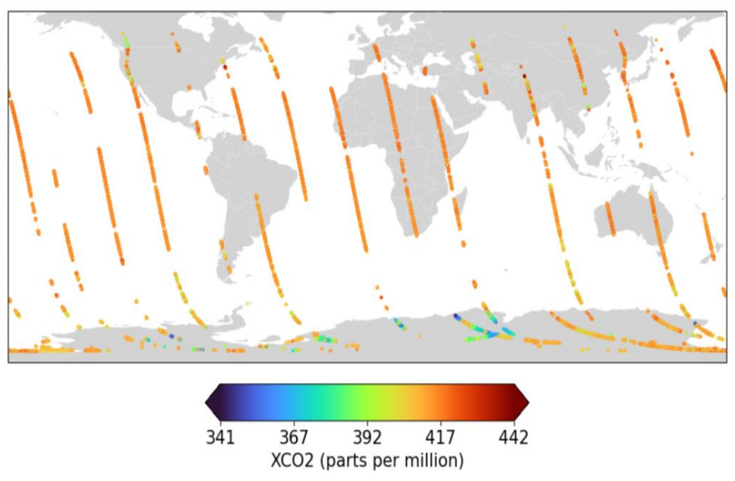

Fig.3
OCO-2 spatial resolution in 1 day.

Satellite Imagery Analysis:

Satellite imagery is analyzed to track land cover changes, fire disturbances, and post-fire regeneration. This aspect of the methodology is crucial for assessing the impact of wildfires on the carbon balance of boreal forests. It allows researchers to quantify the extent, frequency, and intensity of wildfires and their subsequent effects on forest carbon stocks. This analysis helps in understanding the regenerative capacity of the forest and its role in carbon sequestration post-disturbance.
Furthermore, the study will utilize satellite imagery to analyze land cover changes, fire disturbances, and post-fire regeneration. The research aims to combine top-down satellite observations with bottom-up ground measurements to address the frequency, extent, and intensity of wildfires and their subsequent effect on the forest carbon balance.

Objectives

1- Quantify Spatial and Temporal CO2 Exchanges:
Identifying and analyzing the specific periods and geographic areas within Canada's boreal forests where there is a shift between acting as a net carbon sink (absorbing more CO2 than it emits) and a net carbon source (emitting more CO2 than it absorbs). By utilizing satellite-based XCO2 (atmospheric carbon dioxide) data, this research aims to map out and understand the temporal (seasonal, annual) and spatial (location-specific) variations in CO2 fluxes. This involves analyzing satellite imagery and data over time to detect patterns and trends in carbon exchange, thereby identifying key areas and times when the forest's carbon balance tips from negative (sink) to positive (source). This detailed mapping will provide a clearer picture of the forest's role in global carbon dynamics and help identify regions and times that are critical for targeted conservation and management efforts.

2- Analyze Drivers Influencing CO2 Exchanges Variability:
The second objective aims to dissect and understand the various factors that cause fluctuations in the CO2 exchange rates of the boreal forest. This includes an in-depth analysis of how the health of vegetation, changes in land cover (such as due to logging or industrial development), and the impacts of wildfires influence the forest's ability to sequester or release carbon.

By examining these drivers, the research intends to uncover the underlying causes of variability in the forest's carbon exchange processes. This could involve studying changes in tree health and density, the extent and recovery of areas affected by wildfires, and how these factors correlate with changes in carbon fluxes.
The goal is to identify actionable levers that can help manage or mitigate these drivers to maintain or enhance the forest's role as a carbon sink.

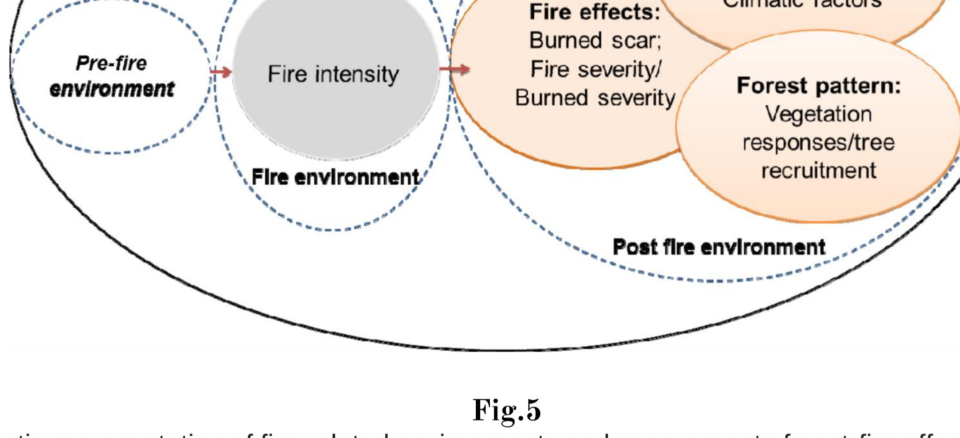

Fig.5
Schematic representation of fire-related environments and assessment of post-fire effects on forest conditions concerning this comprehensive review. This review will particularly focus on studies of post-fire environments with respect to remote sensing approaches.

Adapted from : Chu, T., & Guo, X. (2014). Remote Sensing Techniques in Monitoring Post-Fire Effects and Patterns of Forest Recovery in Boreal Forest Regions: A Review. Remote Sensing, 6(1), 470-520. https://doi.org/10.3390/rs6010470

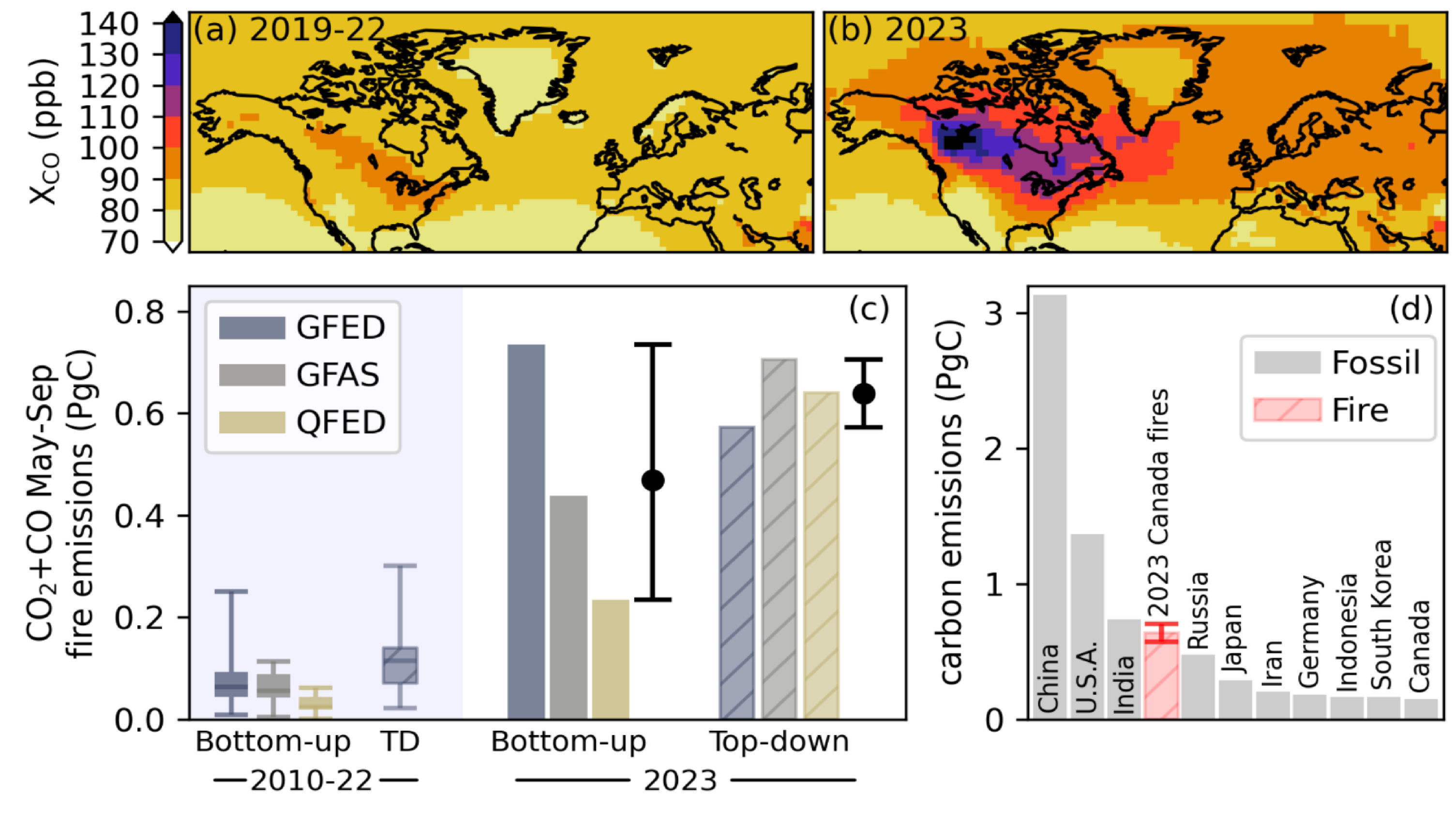

Fig.4. May-Sep TROPOMI XCO (a) averaged over 2019–2022 and (b) for 2023 aggregated to a 2◦ × 2.5◦ grid. (c) Canadian forest fire carbon emissions (from CO and CO2) for the 2023 May-Sep fire season, compared with fire emissions during 2010-2022 (distribution shown by box-and-whisker plots). Top-down emissions over 2010-2022 are estimated from MOPITT (2010–2021) and TROPOMI (2019-2022) CO retrievals. (d) A comparison of May-Sep Canadian fire emissions with 2022 territorial fossil carbon emissions for the 10 largest emitting countries, obtained from Global Carbon Budget 2022.
These estimates are performed using three different prior bottom-up fire emission inventories: the Global Fire Emissions Database (GFED4.1s) , the Global Fire Assimilation System ver- sion 1.2 (GFAS), and the Quick Fire Emissions Data set version 2.6r1 (QFED) inventories.

Adapted from Byrne et al., 2023, Physical Sciences - Article, DOI: 10.21203/rs.3.rs-3684305/v1.

3- Assess Post-Fire Forest Recovery:
The final objective centers on understanding the impact of wildfires on the boreal forest's carbon balance and its recovery process post-disturbance. Wildfires are a natural part of boreal forest ecology but affect the carbon balance by releasing stored carbon and altering the landscape. This research aims to evaluate how these fires impact the forest's carbon sequestration capabilities and to monitor the recovery and regrowth of vegetation using satellite observations. This includes tracking the speed and extent of vegetation regrowth after a fire and how effectively the new growth can sequester carbon compared to pre-fire levels. The aim is to gain insights into the resilience of the forest ecosystem, understand how long it takes for the forest to return to being a net carbon sink after a disturbance, and identify strategies to aid and hasten recovery, thereby mitigating the long-term impact of wildfires on the forest's carbon balance.