Increased Intensity of Carbon Cycle Extremes Driven by Land Use and Land Cover Change

Bharat Sharma[bharat.sharma.neu@gmail.com][1,2], Jitendra Kumar[2], Nathan Collier[2], Auroop R. Ganguly[1], Forrest M. Hoffman[2]

[1]Northeastern University, Boston, Massachusetts 02115, USA; [2]Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

Introduction

- Terrestrial ecosystems account for more than a quarter of the total carbon uptake.
- Climate change has resulted in an increased occurrence of climate extremes such as droughts, heatwaves, fires, storms, and such extremes are expected to further increase with time. These disturbances can weaken the terrestrial uptake strength and can lead to a reduction in carbon stocks, and an increase in the atmospheric CO_2 concentration.
- The extreme events associated with the weakening or strengthening of carbon uptake, also called carbon cycle extremes, can inform us about responsible environmental conditions and increase our understanding and ability to predict future occurrences of such extreme events.
- The overarching goal of this study is to investigate the role of anthropogenic emissions and land use changes in modifying the characteristics of terrestrial carbon cycle extremes and attribution to the individual and compound effects of climate drivers.

Methods

We used the fully coupled simulation configurations, with and without (fixed at year 1850) land use & land cover change (LULCC *(Hurtt el al 2011)*), from Community Earth System Model version 1.0 (CESM1(BGC)) for the time period 1850–2300.

- Historical for 1850–2005,
- Representative Concentration Pathway 8.5 (RCP8.5) for 2006–2100, and
- Extended Concentration Pathway 8.5 (ECP8.5) for 2101–2300.

The simulations were forced with the same prescribed CO_2 mole fraction trajectory as shown in Figure 1.

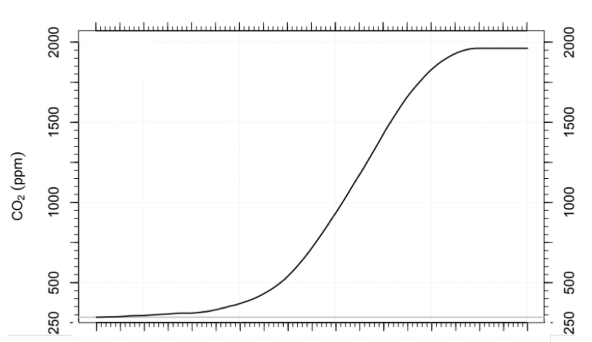


Figure 1: *Prescribed atmospheric CO_2 mole fraction was stabilized at 1962 ppm around the year 2250.*

How do we calculate Carbon Cycle (GPP) Extreme Events?

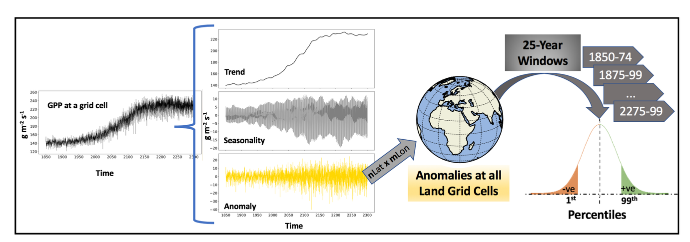
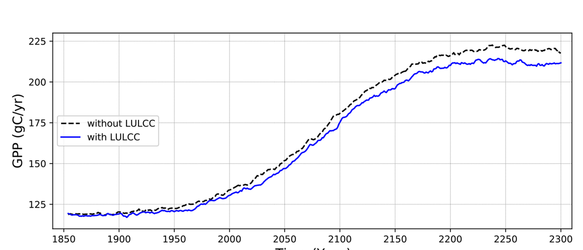


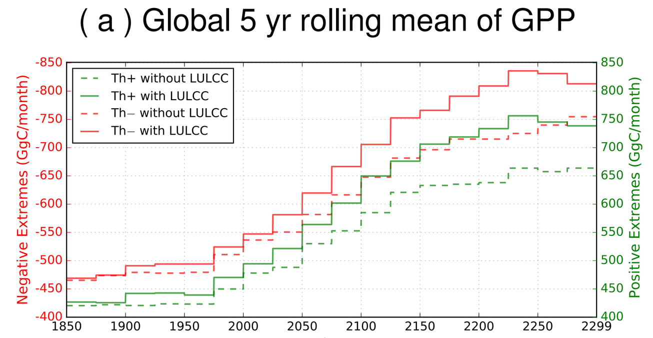
Figure 2: *The anomalies are calculated at every grid cell by subtracting the nonlinear trend and modulated annual cycle from the GPP time series. The anomalies of every land grid cell for consecutive 25 year time windows were chosen to calculate the probability distribution function of GPP anomalies. The 1st and 99th percentile values represent the global GPP threshold values for negative and positive extremes in GPP.*

Negative Carbon Cycle Extreme Events: Represents the events associated with the loss of carbon uptake e.g., decrease in plant productivity, vegetation die back due to droughts, fire, and heat waves. Positive Carbon Cycle Extreme Events: Represents the events associated with gain in carbon uptake e.g., anomalous increase in plant productivity, high vegetation growing season due to increased water availability, optimal growing temperatures.

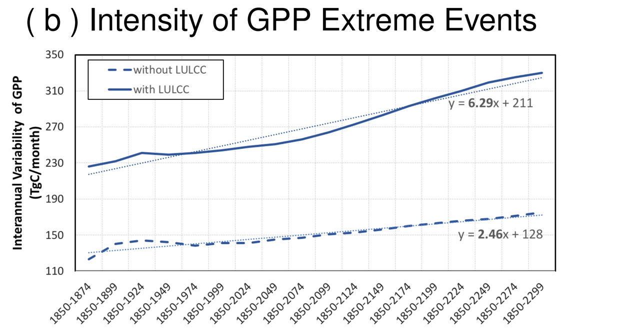
Analysis of Carbon Cycle Extreme Events



(a) Global 5 yr rolling mean of GPP

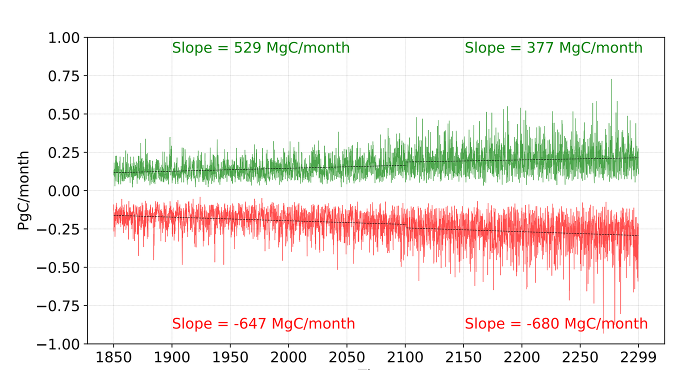


(b) Intensity of GPP Extreme Events

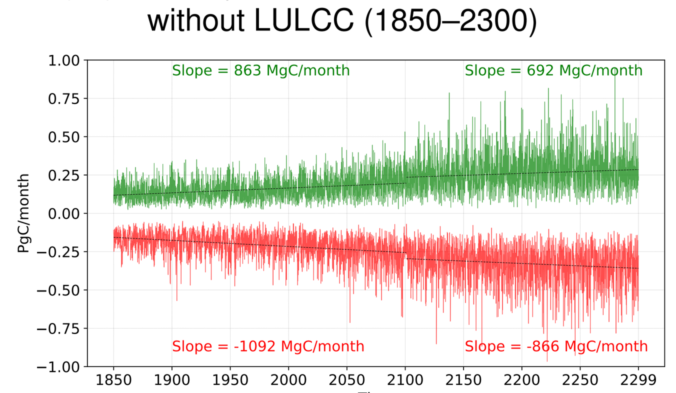


(c) Global interannual variability (IAV) of GPP

Figure 3: *(a) 5 year rolling mean of GPP (PgC/year) for the model configuration with and without Land Use and Land Cover Change for the period 1850–2300. The GPP with LULCC is less than without LULCC, likely due to carbon loss due to wood harvest and conversion of forests to agricultural lands and pastures. (b) Increasing threshold of positive and negative GPP extreme events based on 99th and 1st percentile were mainly driven by increased IAV of GPP (c). Increasing thresholds highlight the unprecedented magnitude of carbon cycle extremes in the future.*

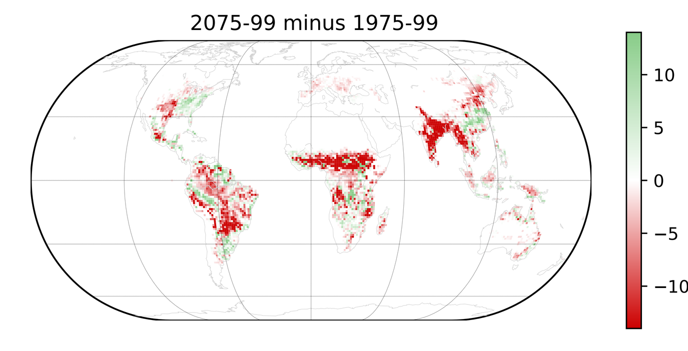


(a) Intensity of the GPP Extreme Events without LULCC (1850–2300)

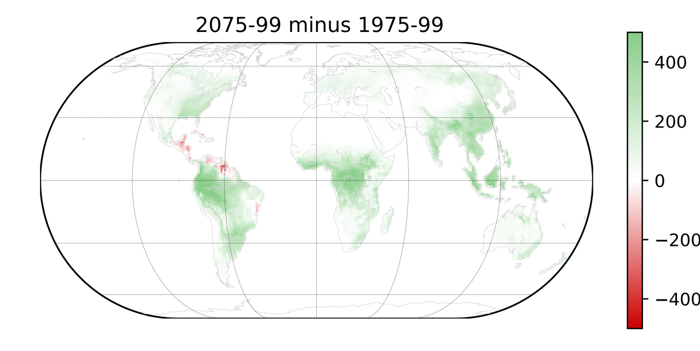


(b) Intensity of the GPP Extreme Events with LULCC (1850–2300)

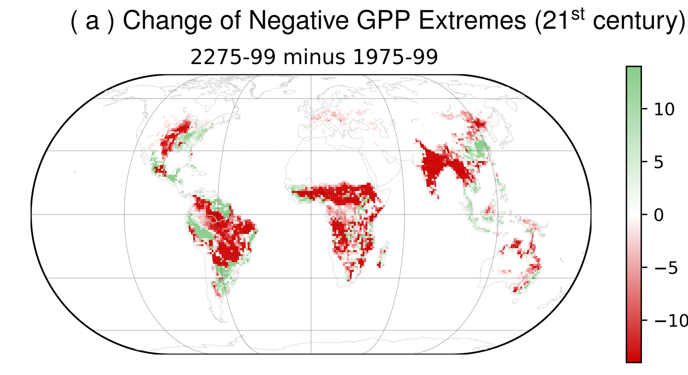
Figure 4: *Monthly time series of intensity of global GPP extreme events for the simulation (a) without LULCC and (b) with LULCC from 1850 – 2299. The positive GPP extremes, GPP anomalies $> q$, are represented in green color and the negative extremes, GPP anomalies $< -q$, are shown in red color. The rate of increase in the intensity of positive and negative carbon cycle are higher for the simulation with LULCC due to the influence of LULCC in altering the climate through biogeochemical and biogeophysical processes. Increased variability of climate results in increasing interannual variability of GPP. The higher rate of negative extremes compared to positive extremes highlights that losses in carbon uptake are higher than gain in carbon uptake.*



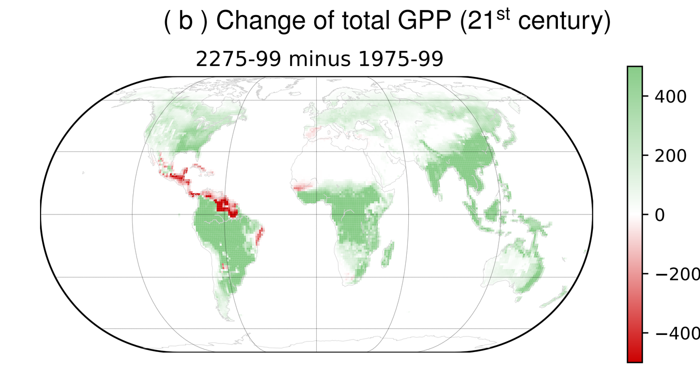
(a) Change of Negative GPP Extremes (21st century)



(b) Change of total GPP (21st century)



(c) Change of Negative GPP Extremes (23rd century)



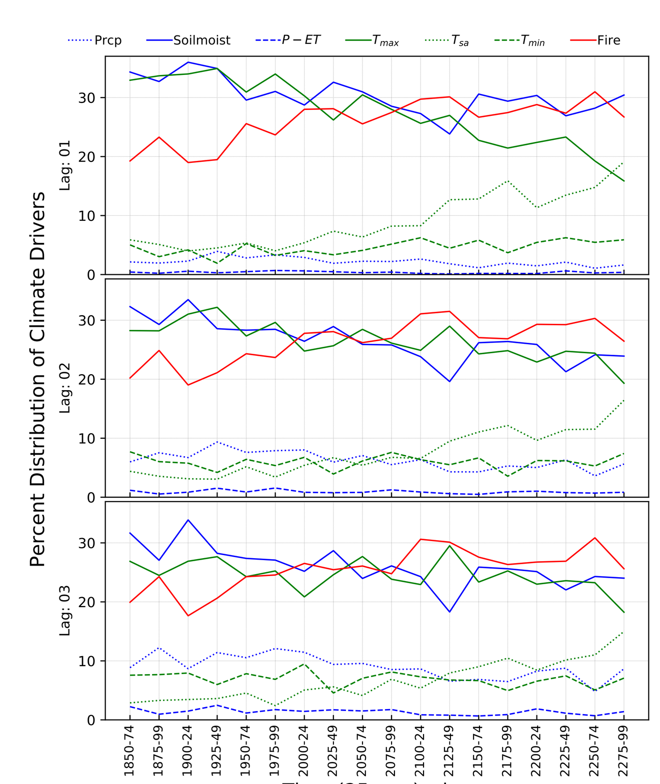
(d) Change of total GPP (23rd century)

Figure 5: *The integrated changes in GPP negative extremes, (a) & (c), and changes in GPP and GPP, (b) & (d), over 25 yr time period are with respect to 1975–99. Red and green color in (a) & (c) indicates the increasing and decreasing intensity of negative extremes respectively. Red and green color in (b) & (d) indicates the loss and increase of vegetation productivity respectively.*

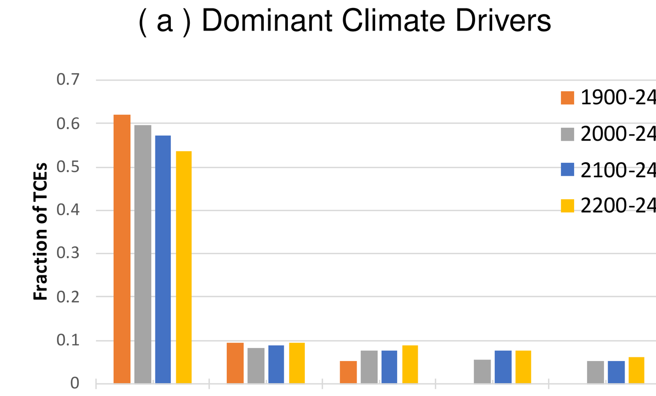
The total number of grid cells and area affected by negative extremes in GPP for the simulation with LULCC were the largest, possibly because of increased negative feedback of climate variability on the carbon cycle due to the cumulative CO_2 and LULCC forcing. With LULCC, growth rates for the area affected by positive GPP extremes were 16% and 28%, and for negative GPP extremes at 12% and 20% during 1850–2100 and 2101–2300 respectively. While the area affected by positive carbon cycle extremes is larger than negative extremes, the magnitude of negative extremes is higher than positive extremes.

Attribution to Climate Drivers

A time continuous extreme event (TCE) is defined as a long-duration event that has at least one continuous 3 month extreme event with a maximum gap of 2 months between other discrete extremes. To attribute the carbon cycle TCE events to climate drivers, the cumulative lagged effect of climate drivers was included to consider the buffer and response of the ecosystem to changing climate drivers. Attribution using TCEs helps us identify large carbon cycle extremes with significant confidence.

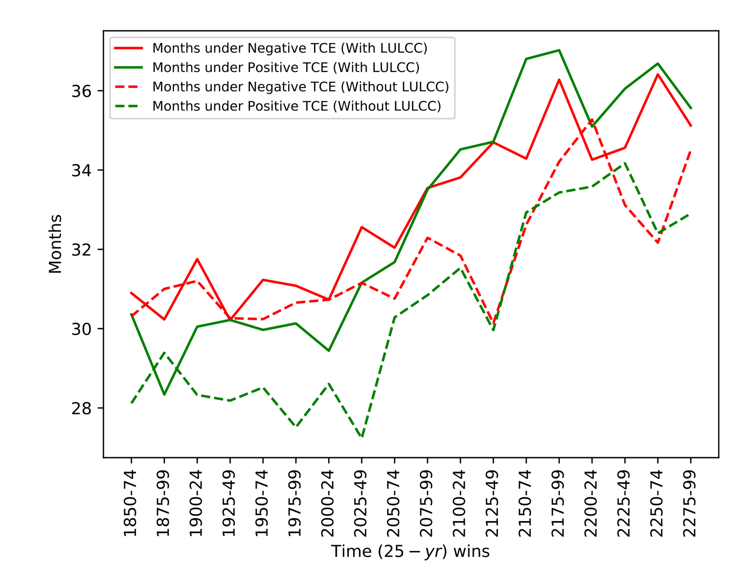


(a) Dominant Climate Drivers

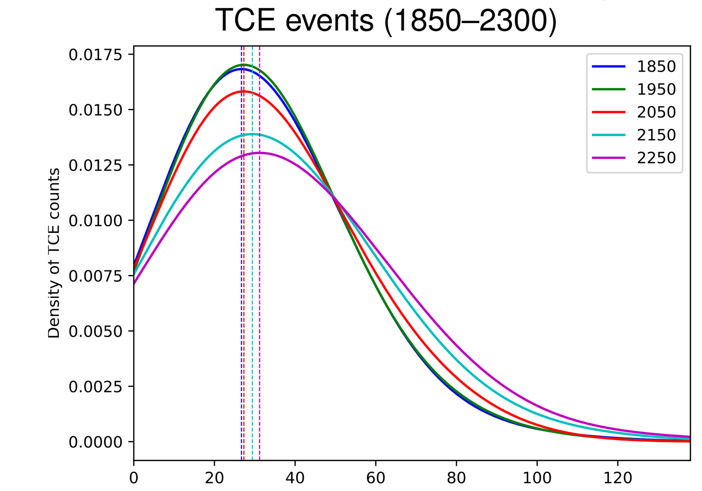


(b) Fraction of GPP TCEs attributed to Compound effect of Climate Drivers

Figure 6: *(a) Percent frequency distribution of global dominant climate drivers leading to carbon cycle TCEs for the simulation with LULCC for every 25 years time window from 1850–2299. A climate driver with highest correlation coefficient (p<0.05) with GPP TCEs at any grid cell is called a dominant climate driver. (b) Attribution of GPP TCEs to compound effect of climate drivers for the simulation with LULCC at lag of 1 month for 25 years time windows. Anomalous water limitation (reduction in soil moisture) leads to dry environment and increase in anomalous temperature lead to dry environment. We show the combination of driving climate drivers that have total fraction of more than 0.05. The combined effect of hot and dry climate accompanied by fire leads to most negative TCE events in GPP.*



(a) The mean duration of carbon cycle TCE events (1850–2300)



(b) PDF of total months under negative carbon cycle TCE events (1850–2300)

Figure 7: *(a) The mean duration of time continuous extreme (TCE) events for every time window from 1850–2299. The figure shows the development of mean duration of positive (shown in green) and negative (shown in red) TCEs for both the simulations, with (solid lines) and without (dashed lines) LULCC. (b) The probability density of TCE counts of total number of months under a negative TCEs in 25 years or 300 months (as shown in x-axis) for 25 year windows starting at the years 1850, 1950, 2050, 2150 and 2250 with LULCC. The dashed vertical lines shows the shifting of mean duration of negative TCEs to right, highlighting that the TCEs are getting longer over time.*

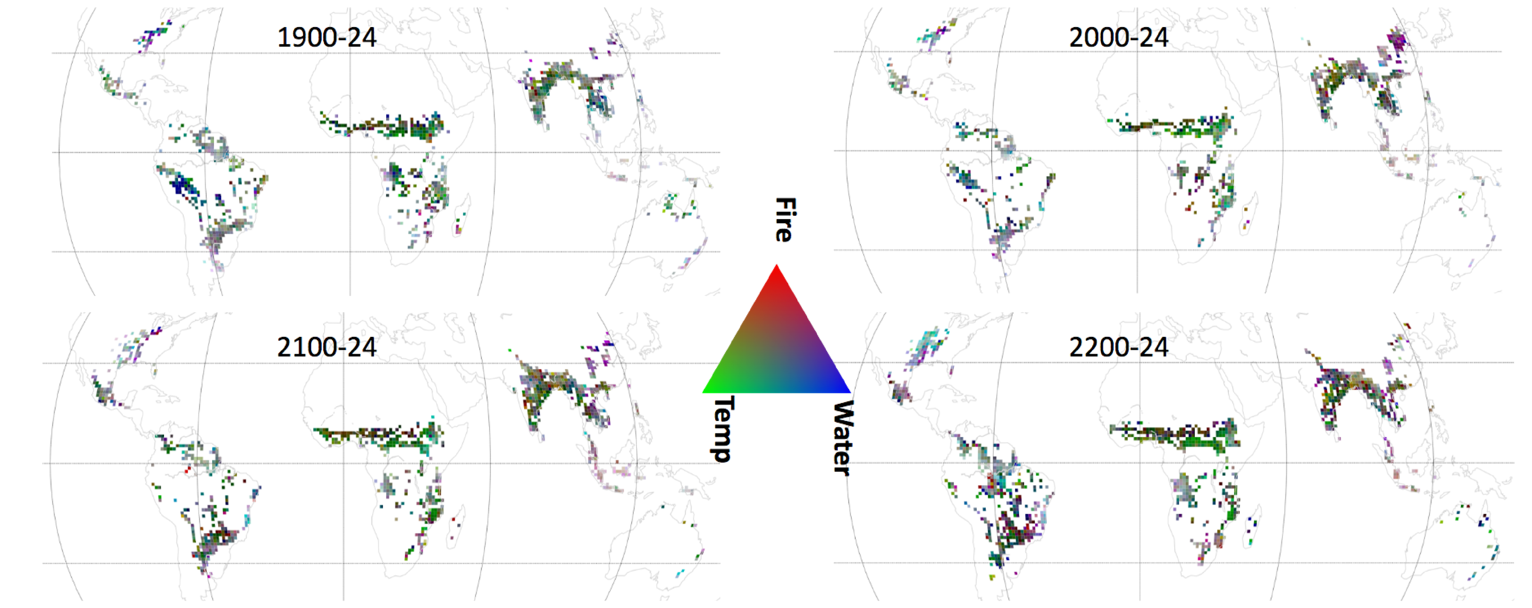


Figure 8: *The spatial distribution of climate drivers which trigger the time continuous GPP negative extremes under without-LULCC scenario for the time period 2000–2024. Blue color represents water related climate drivers (Prcp, P–ET, Soilmoist), Green color represents T_{max}, T_{sa}, T_{min} and Red represents Fire.*

Discussions

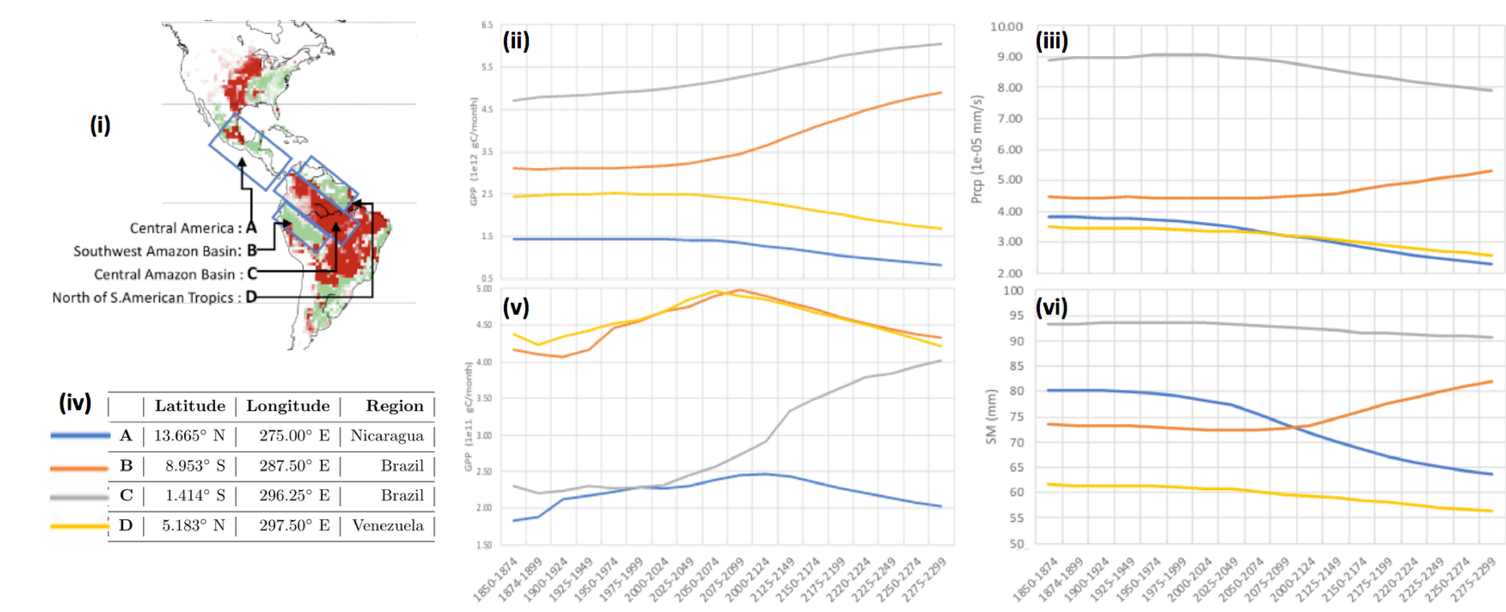


Figure 9: *To discuss the changing pattern of climate driven carbon cycle extremes for the regions shown in (i), we selected a pixel in each region (iv). The time series of GPP (ii), Precipitation (iii), IAV of GPP (v), and Soil Moisture (vi) for the simulation without LULCC is shown. The IAV is calculated from the year 1850 as the base year for every 25-years increments. While the weakening of negative carbon cycle extremes and IAV of GPP in the regions **A,D** is due to decline of precipitation and soil moisture, the region **B** experiences an increase in GPP due to regular precipitation. The region **C** shows the strengthening of negative carbon cycle extremes and increasing IAV of GPP proportional to increases in GPP.*

Conclusions

- The GPP for simulations with LULCC has lesser magnitude than GPP without LULCC implying that increased wood harvest and land conversion impairs vegetation productivity.
- The changes in land cover directly and indirectly causes increased interannual variability in GPP. Hence, results in higher intensity, duration, extent, and frequency of carbon cycle extremes in the simulation with LULCC.
- The future will witness much larger carbon cycle extremes of unprecedented magnitude of net losses in carbon uptake.
- We found that the decline in precipitation triggers a negative carbon cycle TCE event, but the reduction in soil moisture or water limitation was the dominant driver for persisting a negative carbon cycle TCE.
- The fire was the dominant driver, especially after 2100 for simulation with LULCC, highlighting the increased vulnerability of ecosystems to fire events due to human activities' impact on the ecosystems.
- The largest fraction of negative carbon cycle extremes were driven by a compound effect of hot, dry, and fire events.

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Sharma, B., Kumar, J., Collier, N., Ganguly, A. R., & Hoffman, F. M. (2022). Quantifying carbon cycle extremes and attributing their causes under climate and land use and land cover change from 1850 to 2300. Journal of Geophysical Research: Biogeosciences, 127, e2021JG006738. https://doi.org/10.1029/2021JG006738

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