

# Agricultural Green Revolution as a driver of increasing atmospheric CO<sub>2</sub> seasonal amplitude

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## **Objectives:**

- This letter describes an investigation of the relationship of the intensification of agriculture (Green Revolution) during the past five decades with changes in seasonal characteristics of the global carbon cycle during that time, primarily the CO<sub>2</sub> seasonal amplitude.
- The investigators analyzed CO<sub>2</sub> data and atmospheric inversions using a terrestrial carbon cycle model that takes into account high-yield cultivars, fertilizer use, and irrigation.
- The observational data used included the Mauna Loa Observatory CO<sub>2</sub> record from 1958 and a global total CO<sub>2</sub> index from 1981, atmospheric inversions Jena81 and Jena99, and the Carbon Tracker.
- The primary model was the terrestrial carbon cycle model Vegetation Global Atmosphere and Soil (VEGAS) which represents the increase in crop gross primary productivity (GPP) by changes in crop management intensity and harvest index.
- Seasonal amplitude was calculated using standard package CCGRV software from NOAA/ESRL.
- The VEGAS model was run from 1701 to 2010 and forced by observed climate, annual mean CO<sub>2</sub> and land-use management history.
- The authors also included at global total CO<sub>2</sub> index (CO<sub>2</sub><sub>GLOBAL</sub>) and net land–atmosphere carbon flux (F<sub>TA</sub>) from three atmospheric inversions.
- The study also examined the relative concentrations of natural vegetation vs. cropland in driving the rising seasonal amplitude.
- To further delineate the relative contribution of climate, CO<sub>2</sub> fertilization and land use, three additional experiments were used (named CLIM, CO<sub>2</sub>, LU, respectively) in which only one of the three forcings were used as a model driver, while the other two remained fixed.

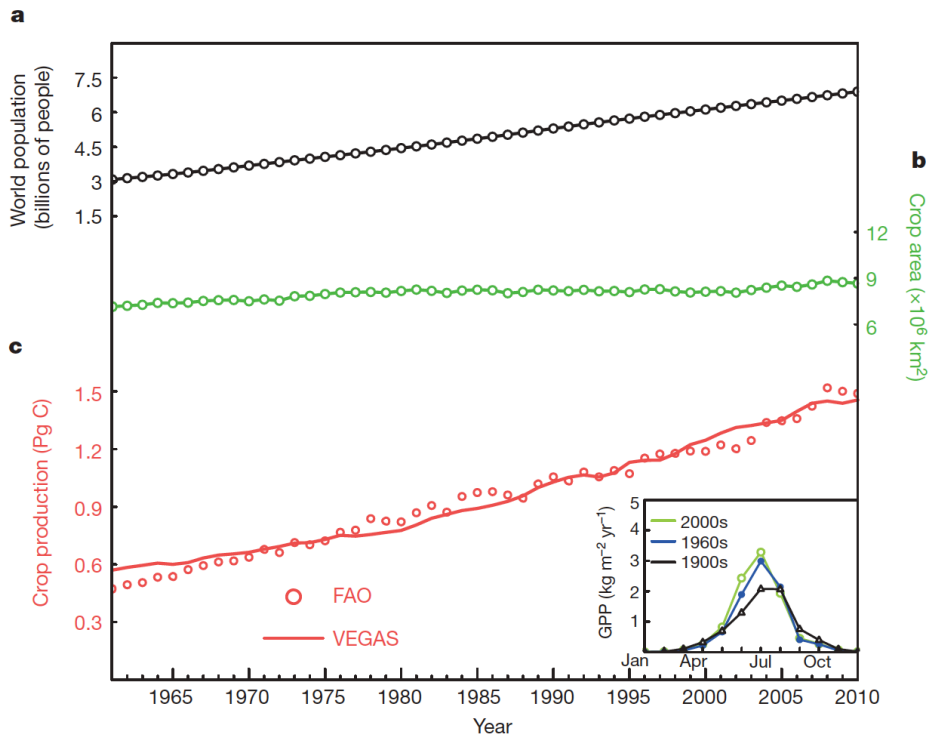
## **New Science:**

- The analysis of CO<sub>2</sub> data and atmospheric inversions shows a 15 percent long-term increase in CO<sub>2</sub> seasonal amplitude from 1961 to 2010, punctuated by large decadal and interannual variations.
- The change in the seasonal CO<sub>2</sub> amplitude is best characterized as a relatively steady long-term increase, modulated by decadal variations, although it can alternatively be viewed as several periods of slow changes or even slight decreases punctuated by large episodic increases.
- The long-term increase in CO<sub>2</sub> seasonal amplitude arises from two major regions: the mid-latitude cropland between 25°N and 60°N and the high-latitude natural vegetation between 50°N and 70° N.
- The long-term trend of seasonal amplitude increase is 0.31160.027 percent per year.
- Sensitivity experiments attribute 45, 29 and 26 percent of the increase to land-use change, climate variability and change, and increased productivity due to CO<sub>2</sub> fertilization, respectively.
- Vegetation growth was earlier by one to two weeks, as measured by the mid-point of vegetation uptake.
- The carbon uptake was 0.5 petagrams greater in July (the height of the growing season) during 2001–2010 than in 1961–1970.
- The seasonal amplitude increase between the two time periods 1961–1970 and 2001–2010 occurs in both the naturally vegetated area and in cropland.
- Over cropland, the seasonal amplitude increased nearly everywhere, while a major increase occurred in Northern Hemisphere natural vegetation between 50°N and 70°N.
- The spatial pattern of the NPP trend shows the largest increase in the Northern Hemisphere agricultural belts of North America, Europe and Asia, supporting the interpretation that the intensification of agriculture has a key role in FTA seasonal amplitude change.

## **Significance:**

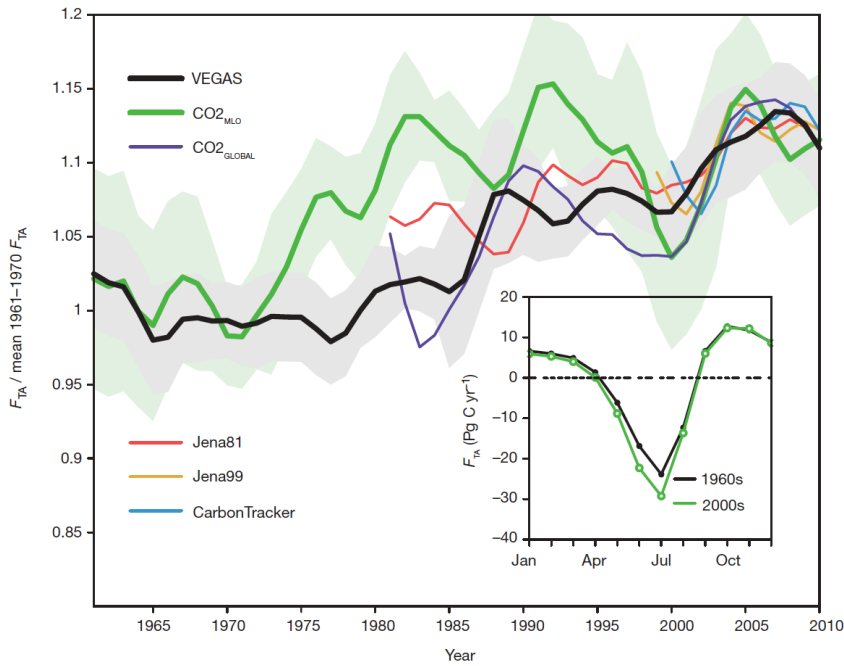
- Atmospheric carbon dioxide (CO<sub>2</sub>) displays a prominent seasonal cycle which arises primarily from changes in vegetation growth and the corresponding CO<sub>2</sub> uptake during boreal growing seasons (spring and summer), and CO<sub>2</sub> release in fall and winter.
- Seasonal amplitude of CO<sub>2</sub> has increased over the past fifty years, suggesting increase in Northern Hemisphere biospheric activity.
- The stimulation of vegetative growth by the mechanisms of higher concentrations of CO<sub>2</sub> and warming, alone, has not explained the full range and magnitude of the observed increase in CO<sub>2</sub> seasonal amplitude.
- The Green Revolution is the time period (since the 1960s) in which a much greater crop yield per unit area was achieved by hybridization, irrigation and fertilization.
- During the 50-year time span studied, crop production tripled from 0.5 petagrams of carbon per year (PgCyr21) to 1.5PgCyr21, while there was only a 20% increase in land area of major crops; at the same time, the world population more than doubled.
- Cropland is often considered less productive than the natural vegetation they replace, so the results that show cropland having such a large impact is noteworthy.
- This large impact on crops to the increased seasonal amplitude is due primarily to high productivity.
- The VEGAS model broadly captures the peak of high productivity of cropland in July, but the other three models analyzed do not do so well.
- A more challenging task for future study would be to explain spatial patterns better, because models may significantly underestimate the high-latitude trend, even if the global total is simulated correctly.
- This study suggests another aspect of human impact on the global carbon cycle: the basic seasonal characteristics of the biosphere, as indicated by atmospheric CO<sub>2</sub> have been modified by human land-management activities.
- The results of this investigation strongly suggest that intensification of agriculture should be included as a driver in carbon cycle models.

**Figure 1 (page 394)**



Changing world population, land area of major crops, annual crop production and changes in crop GPP seasonal cycle. Crop production tripled (a) to support 2.5 times more people (b) on only 20% more cropland area (c), enabled by the agricultural Green Revolution. Plotted in c is the VEGAS model simulated crop production, compared to the estimate from FAO statistics. The insert in c showed modelled CPP for the periods 1901-1910, 1961-1970 and 2001-2010 for a location in the US Midwest agricultural belt (98W-40N) that was initially naturally vegetated and later converted to cropland. The change in seasonal characteristics from these transitions may have contributed to the change in atmosphere CO<sub>2</sub> seasonal amplitude.

**Figure 2 (page 395)**



Temporal evolution of seasonal amplitude. Trends for the VEGAS simulated  $F_{TA}$  (black), of the Mauna Loa Observatory  $CO_2$  mixing ratio ( $CO_{2\_MLO}$ , green) and the global  $CO_2$  mixing ration ( $CO_{2\_GLOBAL}$ , purple), and  $F_{TA}$  from atmospheric inversions of Jena81 (red), Jena99 (brown) and CarbonTracker (blue). Changes are ratios relative to the 1961-1970 mean for VEGAS and the other time series are offset to have the same mean for VEGAS and the other time series are offset to have the same mean for 2001-2010. Seasonal amplitude is calculated as the difference between the maximum and the minimum of each year after detrending and band-pass filtering with a standard tool, CCGCRV. A 7-year bandpass smoothing removes interannual variability whose  $1_s$  standard deviation is shown for  $CO_{2\_MLO}$  (green shading) and VEGAS  $F_{TA}$  (gray shading). The inset shows the average seasonal cycle of VEGAS  $F_{TA}$  for the two periods 1961-1970 and 2001-2010, showing enhanced  $CO_2$  uptake during the spring/summer growing season.