Understanding Aquatic Carbon

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Exercise 1: Aquatic carbon dynamics in the Amazon River Basin: inputs of CO_2 to the atmosphere

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Lesson objective

To use data resources compiled from several major fieldwork campaigns in order to quantify the release of inorganic carbon to the atmosphere (as CO_2) from the Amazon River.

Setting the scene

Rivers transfer huge quantities of dissolved carbon towards the world's oceans, but for some time, researchers were unaware that a large proportion of this carbon escapes to the atmosphere as CO_2 along the way. Understanding this flux at the global scale is important; not only because CO_2 is a greenhouse gas, but also because the quantities involved in terrestrial carbon cycling will be under-estimated if it is not accounted for. Therefore, researchers have sought to understand the global importance of riverine CO_2 "outgassing" by studying the World's greatest rivers. This makes the Amazon a perfect choice, because it drains a vast rain forest ecosystem whose vulnerability to global warming can be better understood as a result.

This exercise is therefore focused on calculating fluxes of carbon that are released as CO_2 from the Amazon to the atmosphere. The CO_2 is mostly derived from forest soil and wetland habitats, before being washed into the river system by rainfall. The calculations require an understanding of the seasonally variable flooded area of the river system and its dissolved CO_2 concentration. Both these variables represent a major challenge to field work and satellite remote sensing on account of the scale of the Amazon Drainage Basin. However, once collected, combining these data into a predictive model is easy, allowing spreadsheet calculations to estimate the quantity of CO_2 released to the atmosphere. Then, we can compare outgassing to other important carbon fluxes in the system, such as net annual production by the forest.

Tasks

1. How does the flooded area of the Amazon Basin change seasonally?

Carbon Dioxide (CO_2) and methane (CH_4) are powerful greenhouse gases whose escape (i.e outgassing or sometimes "evasion") often occurs once the gas molecules have entered a river or lake in direct contact with the atmosphere. The greater the surface area of the water body therefore means more contact with the atmosphere, and so flooding is very important for enhancing outgassing. Immediately, then, there are some important questions to consider:

- Does seasonal rainfall promote seasonality in outgassing?
- How can the surface area of lakes and rivers in the Amazon Basin be quantified?

To understand how the surface area of water in the Amazon varies seasonally and annually, download the Microsoft Excel data sheet 'Evasion model for Amazon'. The purpose of the task is to understand how the evasion of CO_2 from the Amazon river into the atmosphere varies seasonally as the river basin floods. Therefore use tab1 of the worksheet to produce a time series plot of flooded area and establish what sort of flow regime exists.

Q1: Does the flooded area reach a maximum in winter (like the UK) or in summer (like monsoon-driven systems)?

Q2: Which parts of the system provide the greatest flooded area: the main stem of the river and its floodplain, or the multiple tributaries and their floodplains?

The answer to Q2 should be intuitive when you consider the map of the river basin area selected for study and production of these data in Figure 1. Note that not all of the basin could be researched due to problems with satellite data (clouds and trees obscuring the headwater regions).

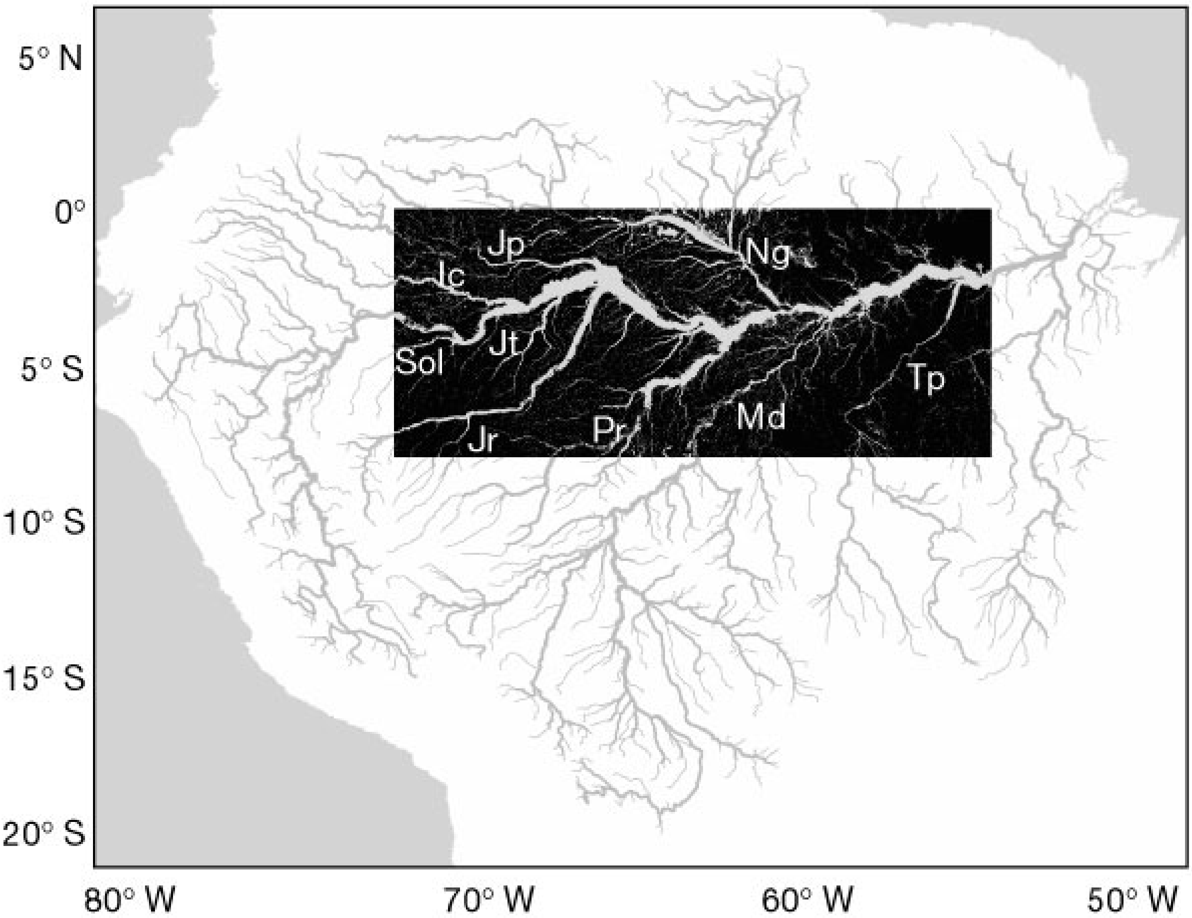

Figure 1 Flooded area of the central Amazon basin at high water, as mapped from the Japanese Earth Resources Satellite radar data (May–June 1996). The flooded area is shown as light areas in a dark inset (the quadrant studied by the researchers). Major tributaries are labelled: Negro (Ng), Japura (Jp), Ica (Ic), Solimoes (Sol, the Amazon mainstem exiting Peru), Jutai (Jt), Jurua (Jr), Purus (Pr), Madeira (Md), and Tapajos (Tp). Data are available for free after registration at NASA's EarthData resource: https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1151.

Outcome: you should have noticed how there is a large seasonal increase in flooded area due to the precipitation regime of the Amazon, causing maximum flooded area in larger tributaries in May, rather like a monsoonal rainfall regime. Since it takes time for the water to enter the main stem of the river, the maximum area here occurs in June. This means that seasonal changes in CO_2 outgassing to the atmosphere are also likely, depending upon the concentration of CO_2 in the water (see below).

2. Seasonal variations in CO_2 outgassing

Now consider the total outgassing of CO_2 into the atmosphere as determined for the first time (Figure 2). The purpose of this task is to help you understand how these results were calculated and to appreciate which factors other than flooded area are important.

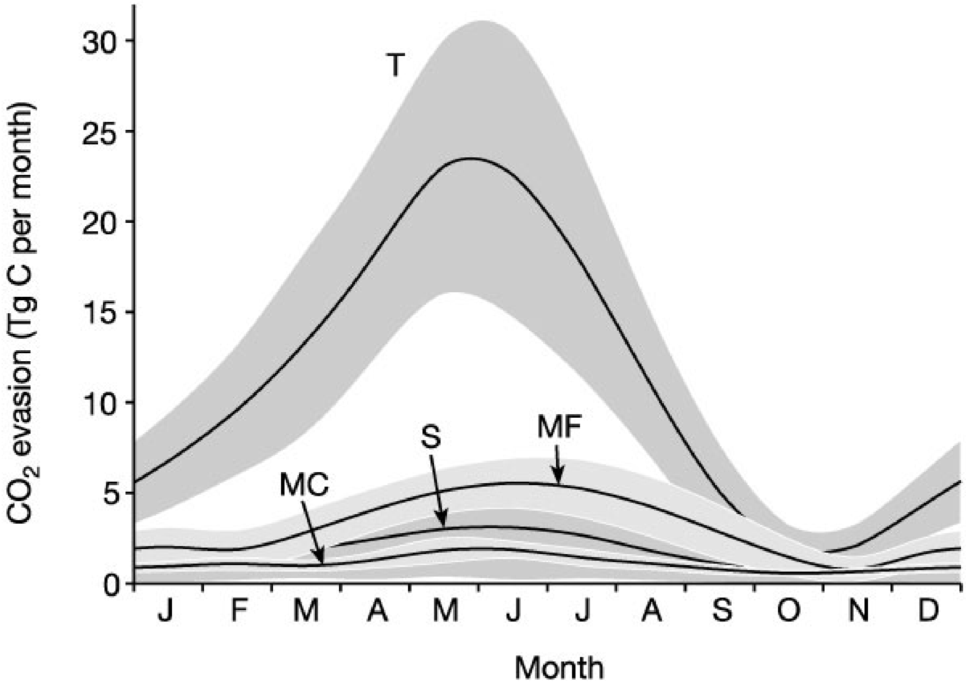

Figure 2. Total CO_2 outgassing from the different elements of the Amazon Basin shown in Figure 1. (Source: Richey et al., 2002). MC is the "main channel", MF is its floodplain, whilst S and T are small and large tributaries respectively (defined as less than or greater than 100 m wide). Units are Tg C per month, or 10^{12} g C (millions of tons).

Figure 2 was produced from the data using a simple mathematical model, of the sort shown in Equation 1:

$$F = A.(0.01).k_{CO2}(\, CO_2^{surface} - CO_2^{equilibrium}) \qquad \textbf{(Eq1)}$$

Where F (g C per time step) is the CO_2 outgassing flux, A is the flooded area (m^2), (0.01) is a constant for unit conversions, k_{CO2} is called the *gas transfer velocity* for CO_2 (units cm h^{-1}) and represents the ease by which CO_2 moves across the water-air interface at different temperature and turbulence conditions, whilst ($CO_2^{surface}$ – $CO_2^{equilibrium}$) represents the CO_2 concentration excess in the water (units mg L^{-1}). The excess concentration therefore increases when CO_2 enters the river. Since outgassing removes the excess, it in effect causes the water to equilibrate with the atmosphere (rather like a fizzy drink going flat). This is why the term "$CO_2^{equilibrium}$" is used to calculate the excess from the observed CO_2 concentrations in surface waters. It is mostly dependent upon the temperature of the water.

$CO_2^{surface}$ was determined by thirteen expeditions along the river, sampling the various tributaries throughout the year and then also measuring concentrations at a fixed, downstream point very regularly for ten years.

k_{CO2}: was estimated from chamber measurements and other studies from more accessible rivers.

3. Calculate F for the Amazon mainstem and tributaries

Open the spreadsheet and on tab2 create a new column with the label "F (Tg C month^{-1})". Then enter Equation 1 as a formula using the columns that represent values for each term. Copy the formula down so that separate calculations are undertaken automatically for each month.

Repeat the exercise using the data for the large and small tributaries. These should closely (but not exactly) match curves T and S in Figure 2, whilst your initial calculations will represent the sum of MC and MF from Figure 2. Ignore minor differences because the data set has been sampled and average values used to simplify the number of calculation steps.

Q4. What makes the contributions from the three sets of surface waters different? Is it all due to flooded area, or are differences in the CO_2 concentrations and K_{CO2} important too?

Q5. Does F (outgassing) respond to A (flooded area) in a linear way? This is important because different years have different floods. Produce a scatter plot of A (X axis) versus F (Y axis) for one of the surface water types. Use the trendline function to add a linear regression model to the data. Compare the r^2 value from this type of regression model to that for a non-linear (i.e. curved) model (try the power function and the exponential models).

Outcome:
You should find that both flooded area and the excess CO_2 concentration increase in summer and so multiplying these terms together enhances the seasonality markedly. The main reason that the large tributaries make such a significant contribution however, is that they cover a large area. Otherwise, they have similar CO_2 values to the main stream.

The r^2 values should be high, indicating that a great proportion of the monthly variations can be explained by flooded area. However, if you find that the positive, exponential relationship or power function between flooded area and outgassing is best, then you have discovered a non-linear, positive feedback to precipitation. In other words, the response gets greater and greater each time the flooded area increases further. Do you think the same effect could be expected if the flooded area was increased by impounding the river, rather than high levels of rainfall?

4. Calculating total annual outgassing and comparing to other terms in the Amazon Rain Forest Carbon Budget

The total riverine outgassing flux of CO_2 can be compared to estimates of dissolved carbon export by the river, or even net rain forest production, provided the same areas of the Amazon Basin area are compared and the same units are employed. In this way you can get a feel for the importance of the process you have just quantified.

Q6. Compare the sum of the monthly outgassing for the entire Amazon Basin with published estimates of other important carbon fluxes associated with the rain forest ecosystem and Amazon River (Table 1). Note that, while your estimate should be about 205 TgC yr^{-1}, it becomes 470 TgC yr^{-1} when scaled up to the entire Amazon Basin (see Fig 1).

Flux	TgC yr^{-1}
Total Amazonian outgassing flux[1]	470
Total riverine dissolved inorganic carbon flux to sea[1]	36
Total riverine dissolved organic carbon flux to sea[1]	35
Long-term average NEP undisturbed forest[2]	-390
Total forest biomass in Amazon[3]	175 000

Table 1. Carbon fluxes and storage in the Amazon Basin. “NEP” is net ecosystem production, with a negative sign indicating the removal of carbon from the atmosphere. (Sources: [1]Richey et al, 2002; [2]Gatti et al, 2014; [3]Nobre et al, 2016).

Outcome: You should appreciate that while the “standing stock” or biomass of the Amazon rain forest is more than a thousand times greater than the outgassing flux, the Net Ecosystem Production is much closer. In fact outgassing puts more CO_2 into the atmosphere than net carbon fixation is able to remove from it. Therefore the outgassing flux represents one of the most important processes.

References:

Gatti, L.V. and others. 2014. Drought sensitivity of Amazonian carbon balance revealed by atmospheric measurements, *Nature*, 506, 76 – 80, doi:10.1038/nature12957.

Nobre, C.A. and others. 2016. Land-use and climate change risks in the Amazon and the need of a novel sustainable development paradigm, *PNAS* 113, 10759–10768, doi/10.1073/pnas.1605516113

Richey, J.E. and others. 2002. Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO_2, *Nature* 416, 617-620, doi:10.1038/416617a

Data Resources:

The data used in Richey et al’s original study are available for download from the NASA EarthData resource: https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1151

Accessing the data is free but requires registration.