

**Variations of dissolved greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) in  
the Congo River network overwhelmingly driven by fluvial  
wetland connectivity**

**Alberto V. Borges**





## **Lab presentation**

## Lab presentation

- ULiège = small oceanography Dept, no limnology Dept
- Lab = 2 permanent researchers, 6 Post-docs, 4 PhD students
- Measurements of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O in aquatic environments
- Inland waters, coastal waters, oceanic waters & marine cryosphere
- Versatile, compact and rugged equipment for harsh environments
- Personal emphasis on African lakes and rivers





## **CO<sub>2</sub> emissions from rivers**

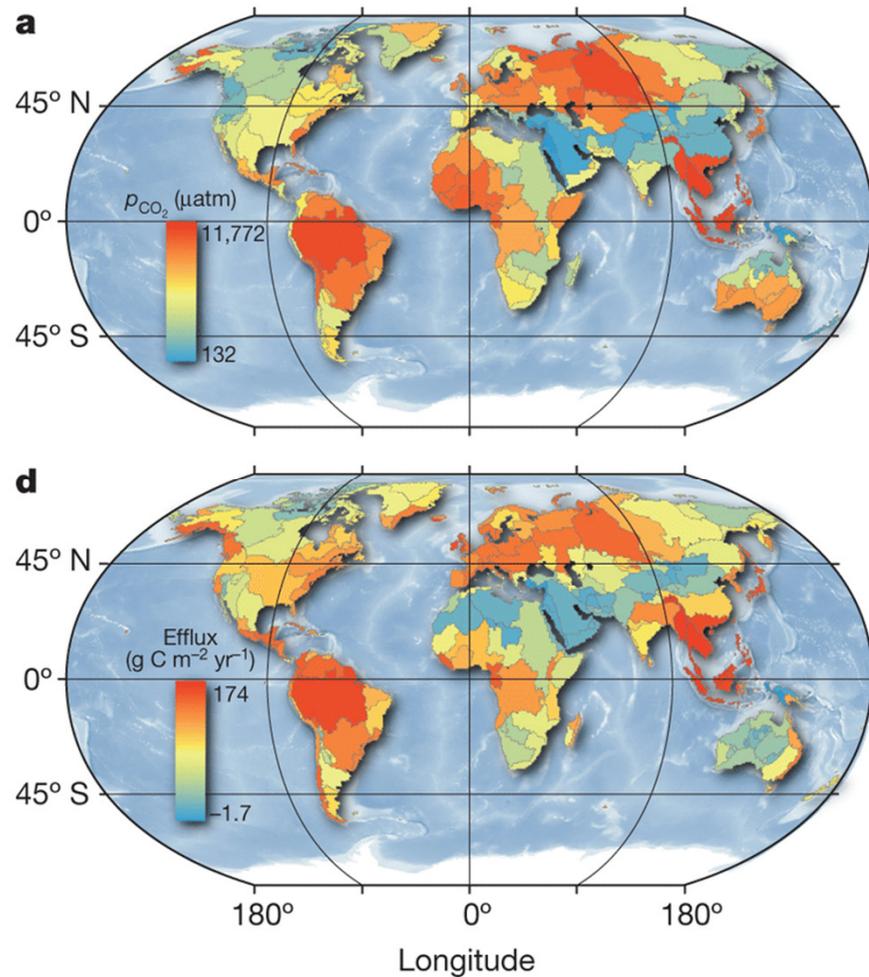
# Global carbon dioxide emissions from inland waters

Peter A. Raymond<sup>1</sup>, Jens Hartmann<sup>2\*</sup>, Ronny Lauerwald<sup>2,3\*</sup>, Sebastian Sobek<sup>4\*</sup>, Cory McDonald<sup>5</sup>, Mark Hoover<sup>1</sup>, David Butman<sup>1,6</sup>, Robert Striegl<sup>6</sup>, Emilio Mayorga<sup>7</sup>, Christoph Humborg<sup>8</sup>, Pirkko Kortelainen<sup>9</sup>, Hans Dürr<sup>10</sup>, Michel Meybeck<sup>11</sup>, Philippe Ciais<sup>12</sup> & Peter Guth<sup>13</sup>

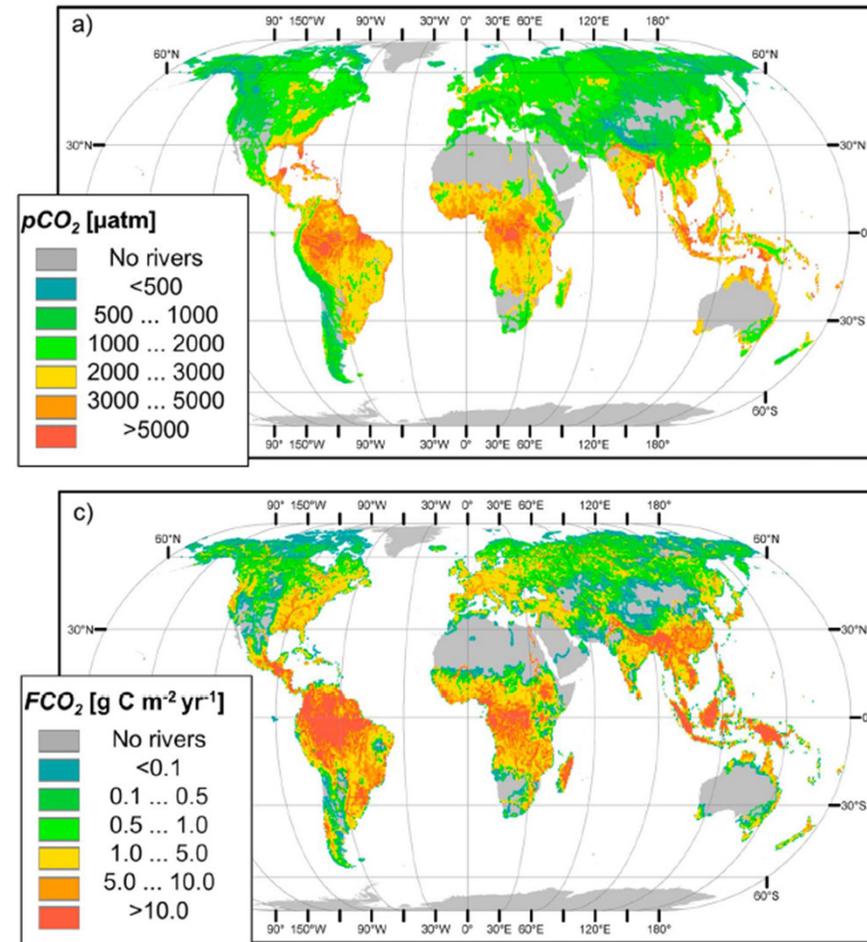
Carbon dioxide (CO<sub>2</sub>) transfer from inland waters to the atmosphere, known as CO<sub>2</sub> evasion, is a component of the global carbon cycle. Global estimates of CO<sub>2</sub> evasion have been hampered, however, by the lack of a framework for estimating the inland water surface area and gas transfer velocity and by the absence of a global CO<sub>2</sub> database. Here we report regional variations in global inland water surface area, dissolved CO<sub>2</sub> and gas transfer velocity. We obtain global CO<sub>2</sub> evasion rates of  $1.8^{+0.25}_{-0.25}$  petagrams of carbon (PgC) per year from streams and rivers and  $0.32^{+0.52}_{-0.26}$  PgC yr<sup>-1</sup> from lakes and reservoirs, where the upper and lower limits are respectively the 5th and 95th confidence interval percentiles. The resulting global evasion rate of 2.1 PgC yr<sup>-1</sup> is higher than previous estimates owing to a larger stream and river evasion rate. Our analysis predicts global hotspots in stream and river evasion, with about 70 per cent of the flux occurring over just 20 per cent of the land surface. The source of inland water CO<sub>2</sub> is still not known with certainty and new studies are needed to research the mechanisms controlling CO<sub>2</sub> evasion globally.

# Introduction

Raymond et al. (2013)

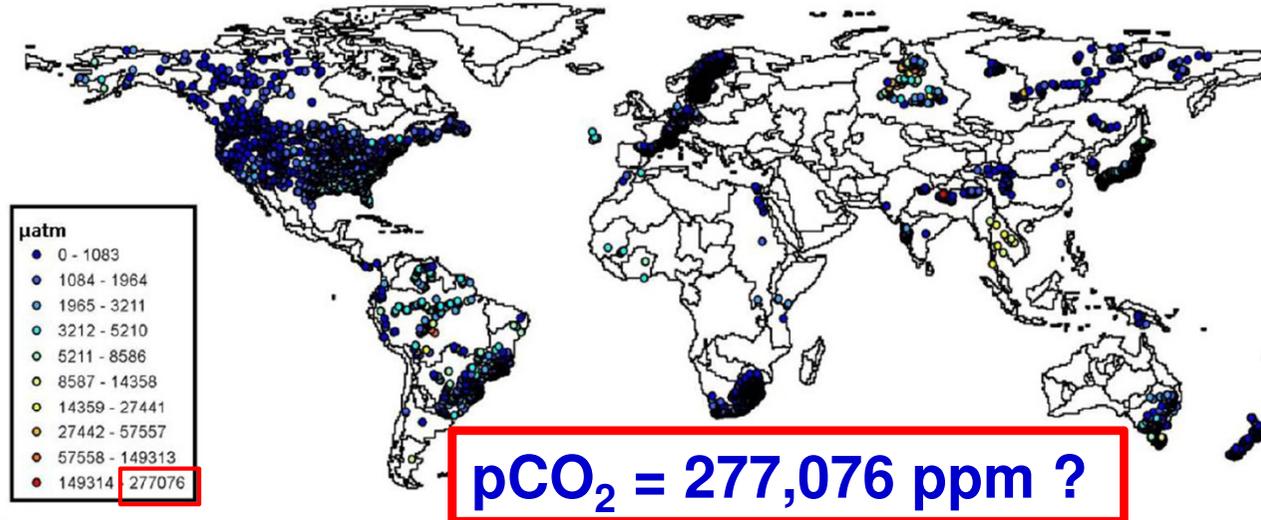


Lauerwald et al. (2015)

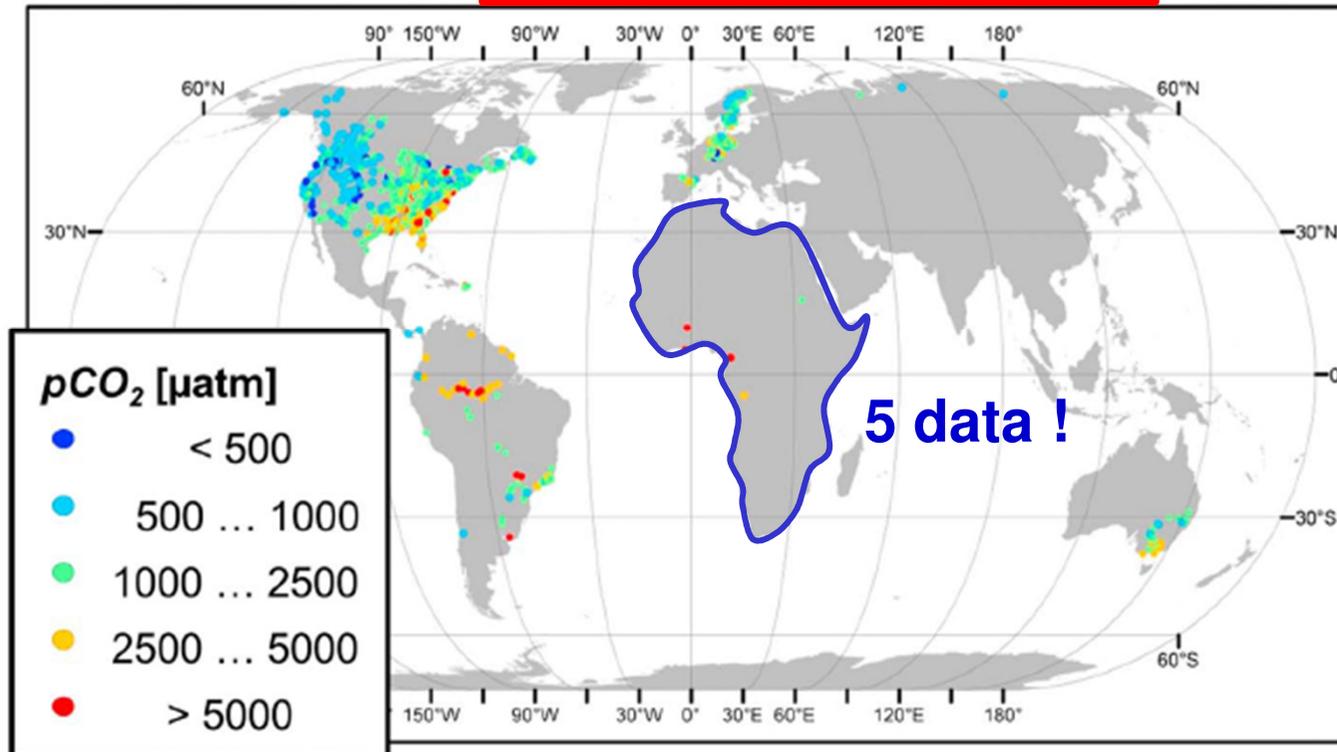


# Introduction

Raymond et al. (2013)

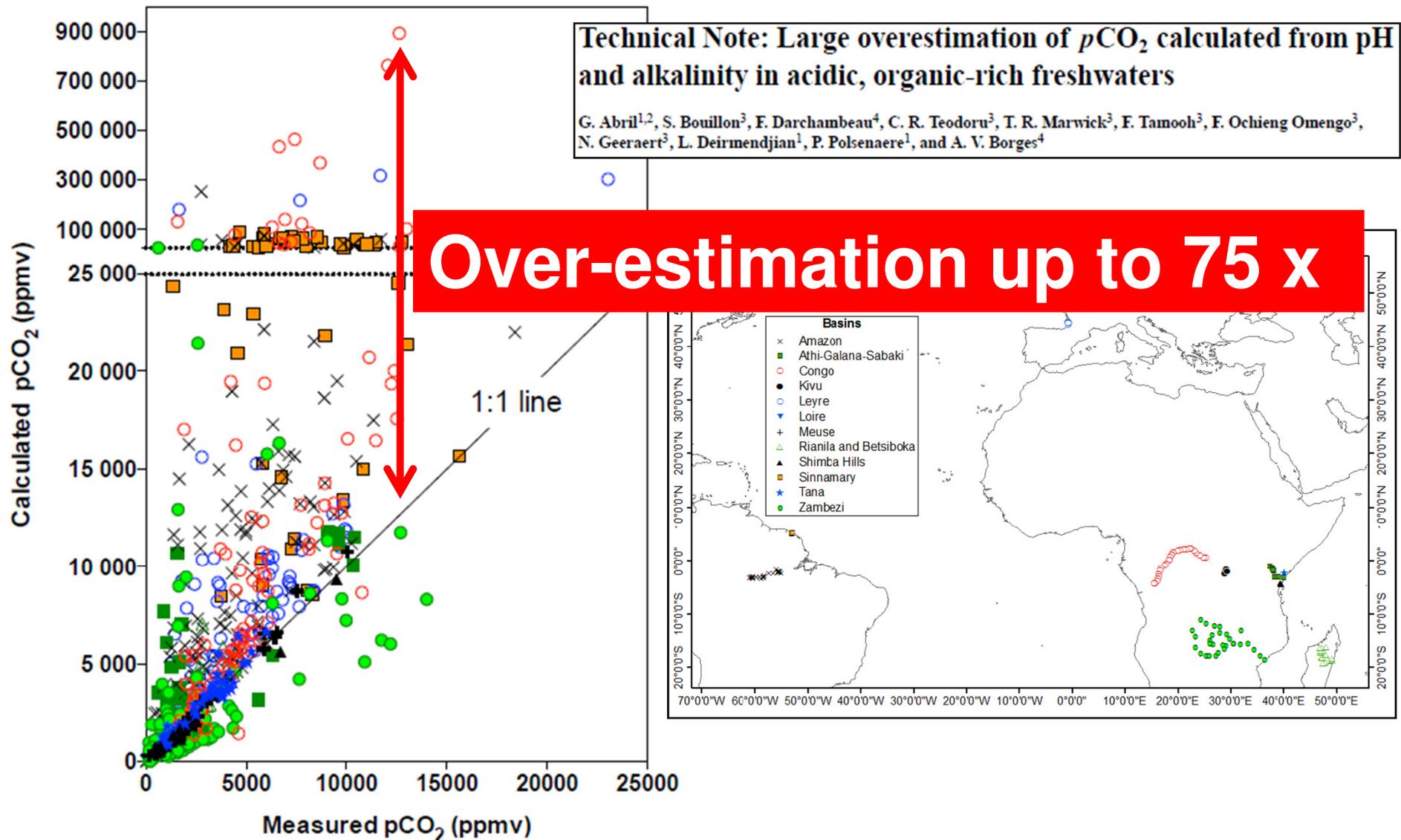


Lauerwald et al. (2015)



# Introduction

Raymond et al. (2013) & Lauerwald et al. (2015) used  $p\text{CO}_2$  computed from pH and total alkalinity



# Introduction

## Tropical Rivers:

- Highest CO<sub>2</sub> emissions
- Lowest data coverage
- Lowest confidence in pCO<sub>2</sub> computed from pH & TA



**Congo river**

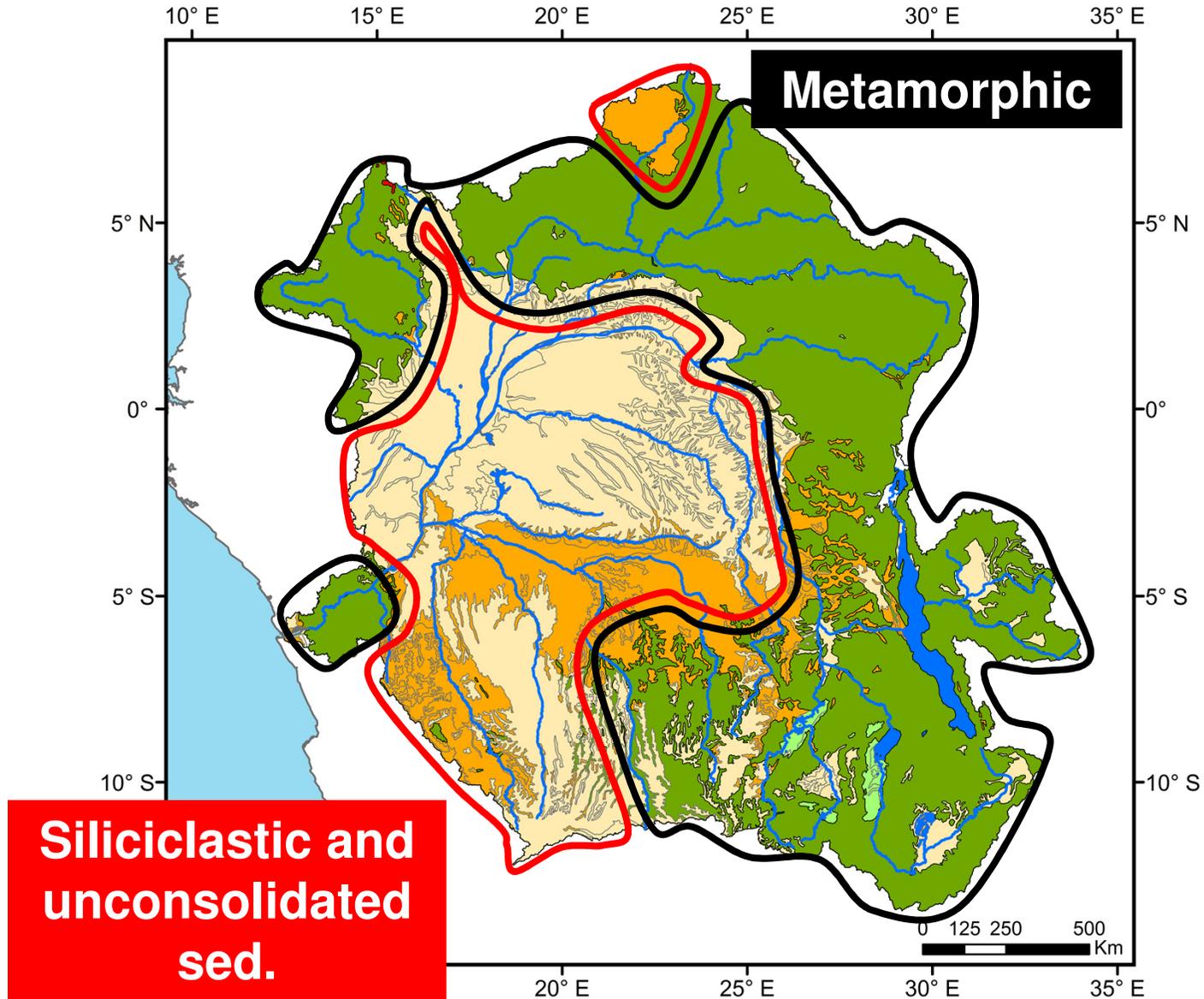
# Congo



# Congo



# Congo



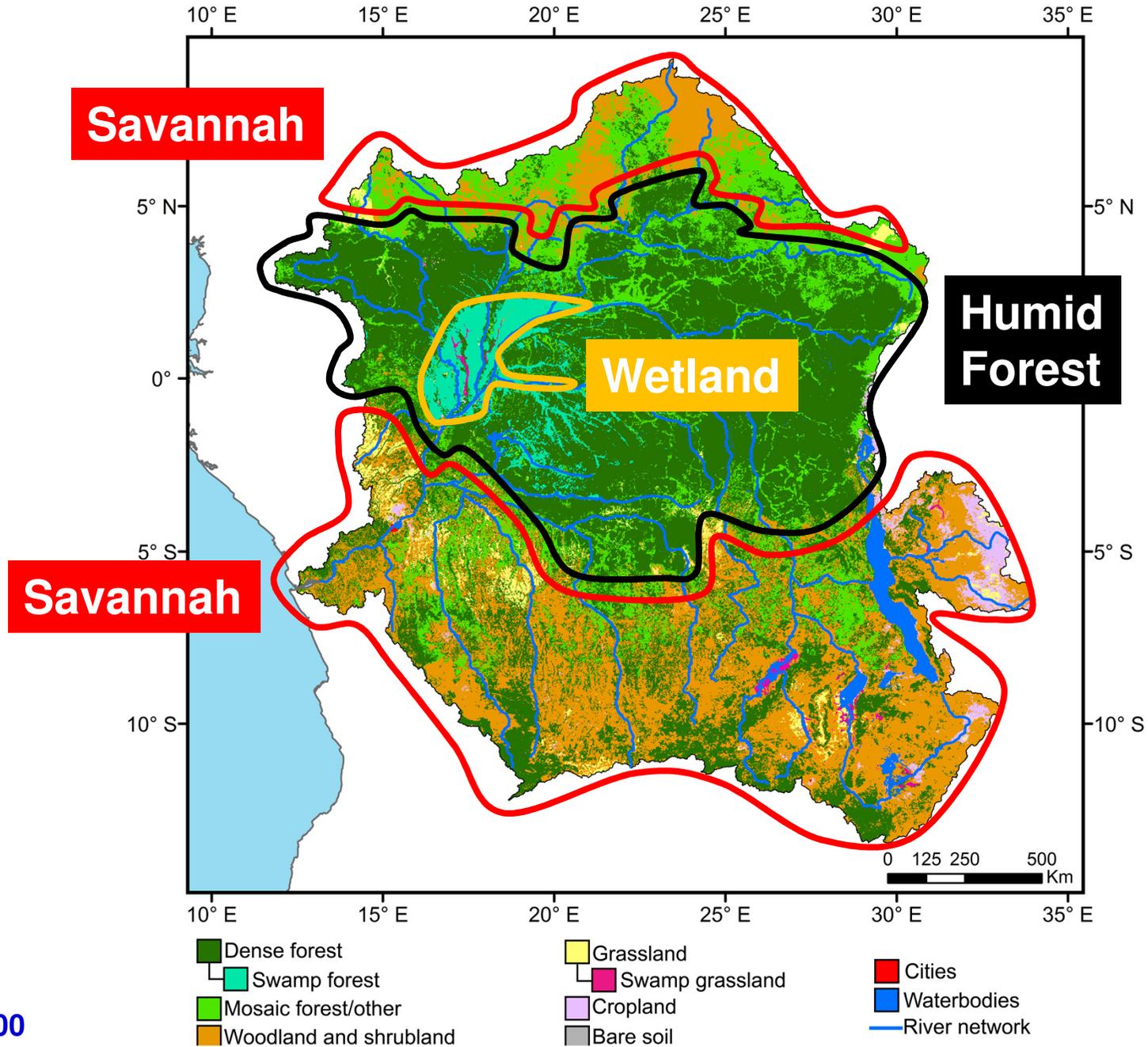
**Siliciclastic and unconsolidated sed.**

**Metamorphic**

- Evaporites
- Acid plutonic
- Siliciclastic sedimentary
- Metamorphic
- Unconsolidated sed.
- Waters bodies

Courtesy of J. Hartmann

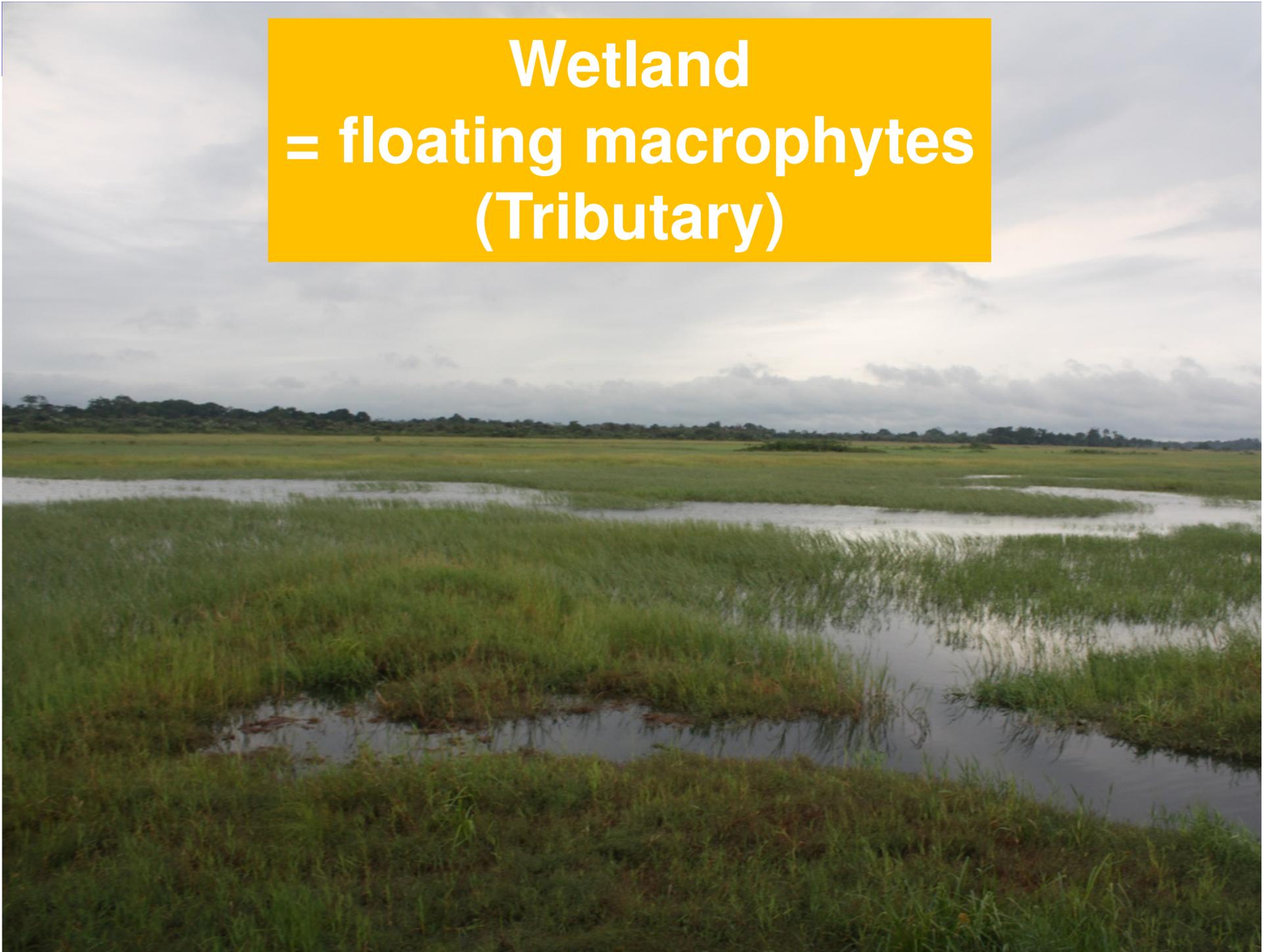
# Congo



**Wetland  
= flooded forest  
(Tributary)**



**Wetland  
= floating macrophytes  
(Tributary)**



**Wetland**  
**= floating macrophytes**  
**(Congo mainstem)**



# Congo

***Azolla pinnata***



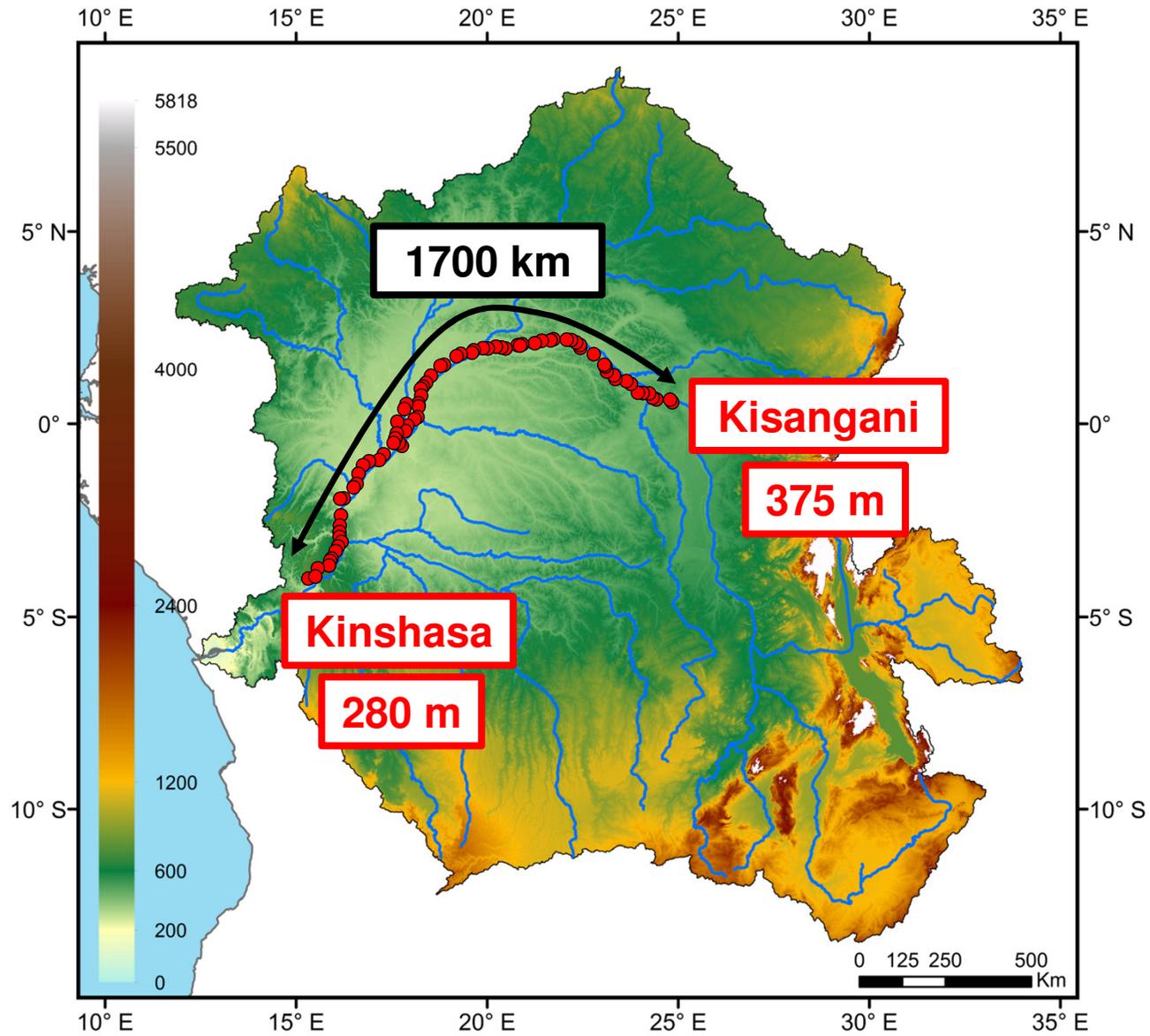
***Vossia cuspidata***  
« Hippo grass »

***Eichhornia crassipes***  
« water hyacinth »



***Salvinia auriculata***

# Congo



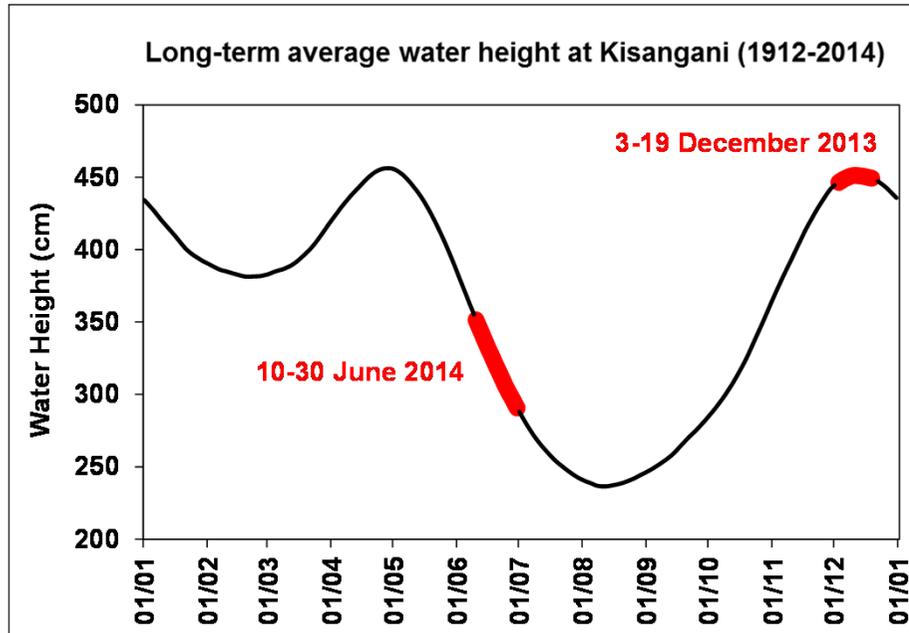
# Congo

The screenshot displays a navigation application interface. On the left, a blue sidebar contains a menu icon, a home icon, and a selection of transport modes: car (selected), train, pedestrian, bicycle, and airplane. Below these are input fields for the start location 'Liège' and the end location 'Madrid, Espagne', with a swap icon. A '+ Ajouter une destination' option is also present. At the bottom of the sidebar, there is a 'Partir maintenant' button and an 'OPTIONS' link.

The main map area shows a satellite view of Western Europe. A blue route is plotted from Liège, Belgium, through France, and ending in Madrid, Spain. A callout box over the route indicates a travel time of '23 h 30 min' and a distance of '1 610 km'. A warning icon (a triangle with an exclamation mark) is placed on the route in France, with a text box below it stating 'Cet itinéraire traverse le pays suivant : France.' Below the main map, there is a 'Satellite' button and a small satellite image preview.

Key locations visible on the map include: Amsterdam, Londres, Pays-Bas, Bruxelles, Cologne, Liège, Luxembourg, Paris, France, Suisse, Monaco, Andorre, Barcelone, Espagne, Madrid, Valence, Portugal, Porto, Lisbonne, Séville, Grenade, and Alger.

# Cruises & Methods



**164 stations  
29 variables**



**> 23,000 continuous measurements  
pCO<sub>2</sub>, cond, temp, pH, O<sub>2</sub>, TSM, cDOM**



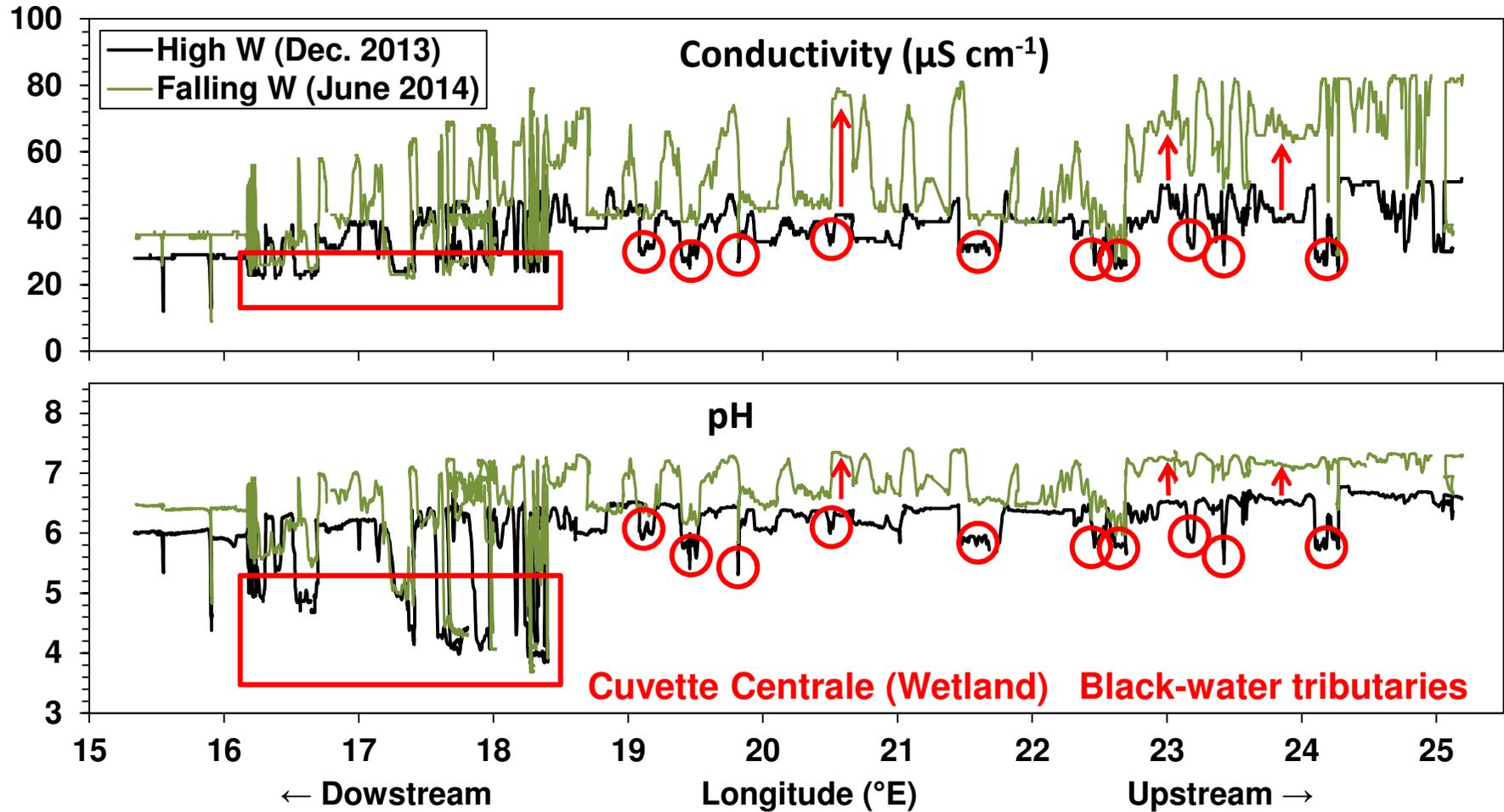
# Cruises & Methods



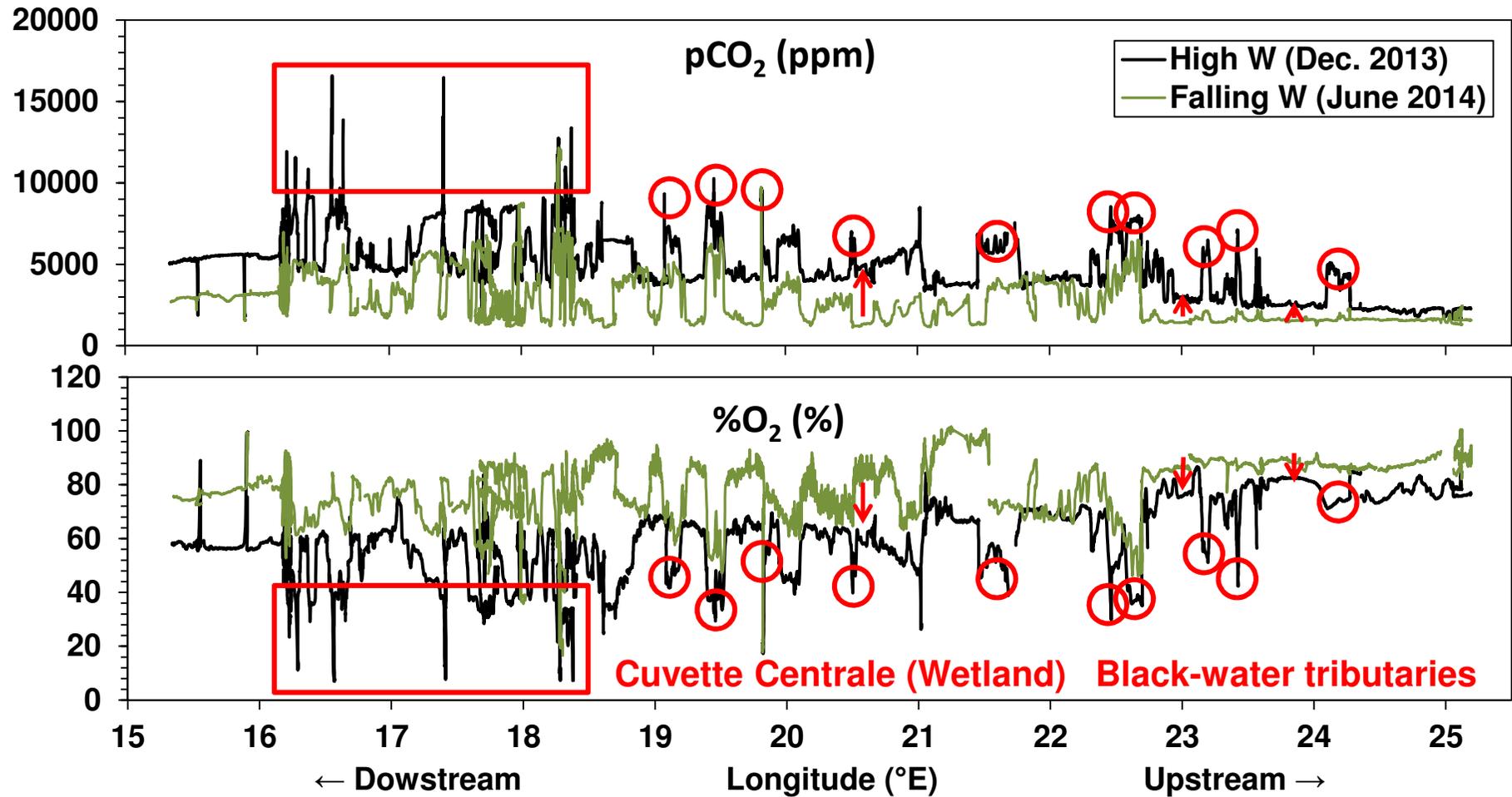
# Results

**Spatial variations of CO<sub>2</sub>**

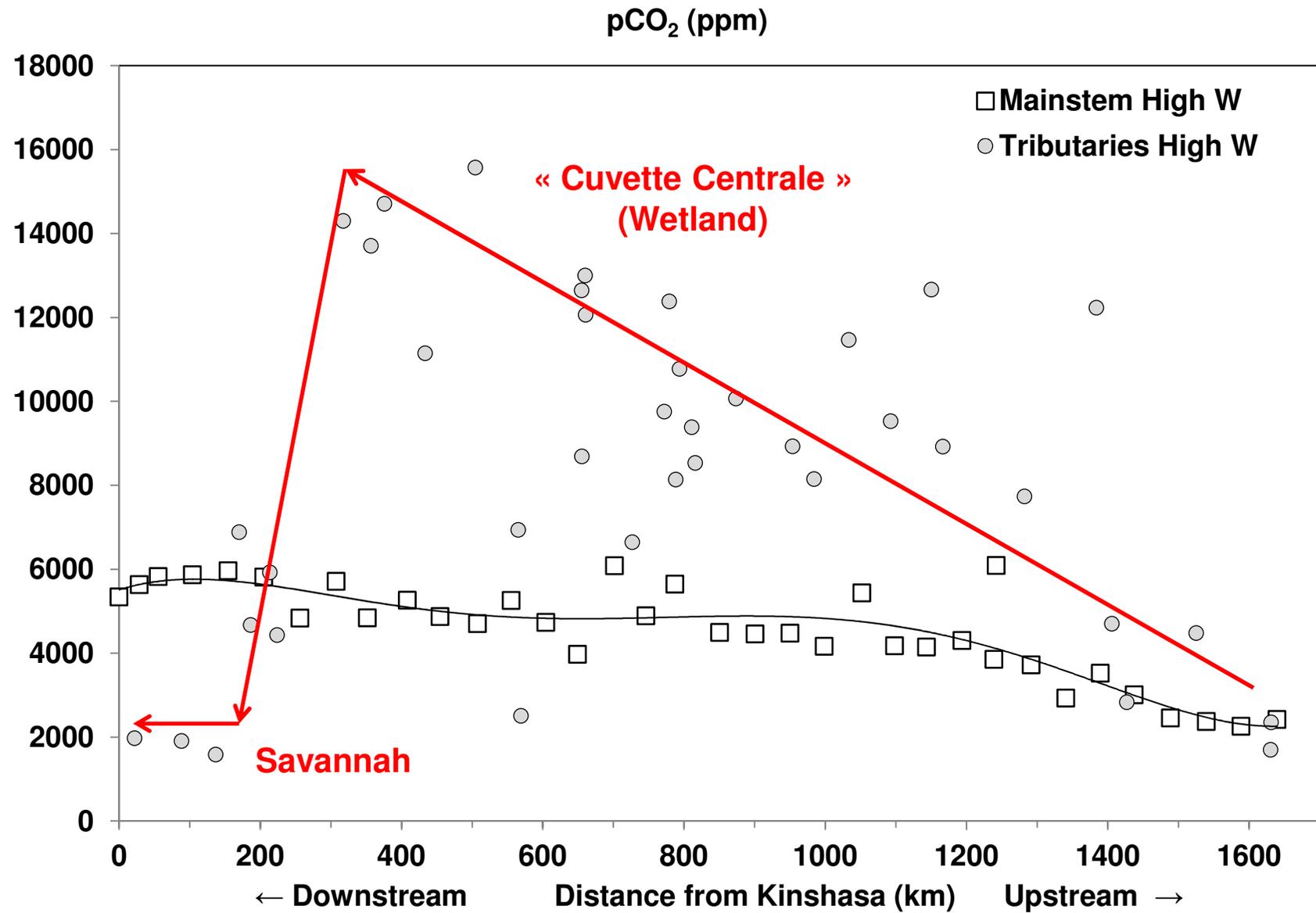
# Results



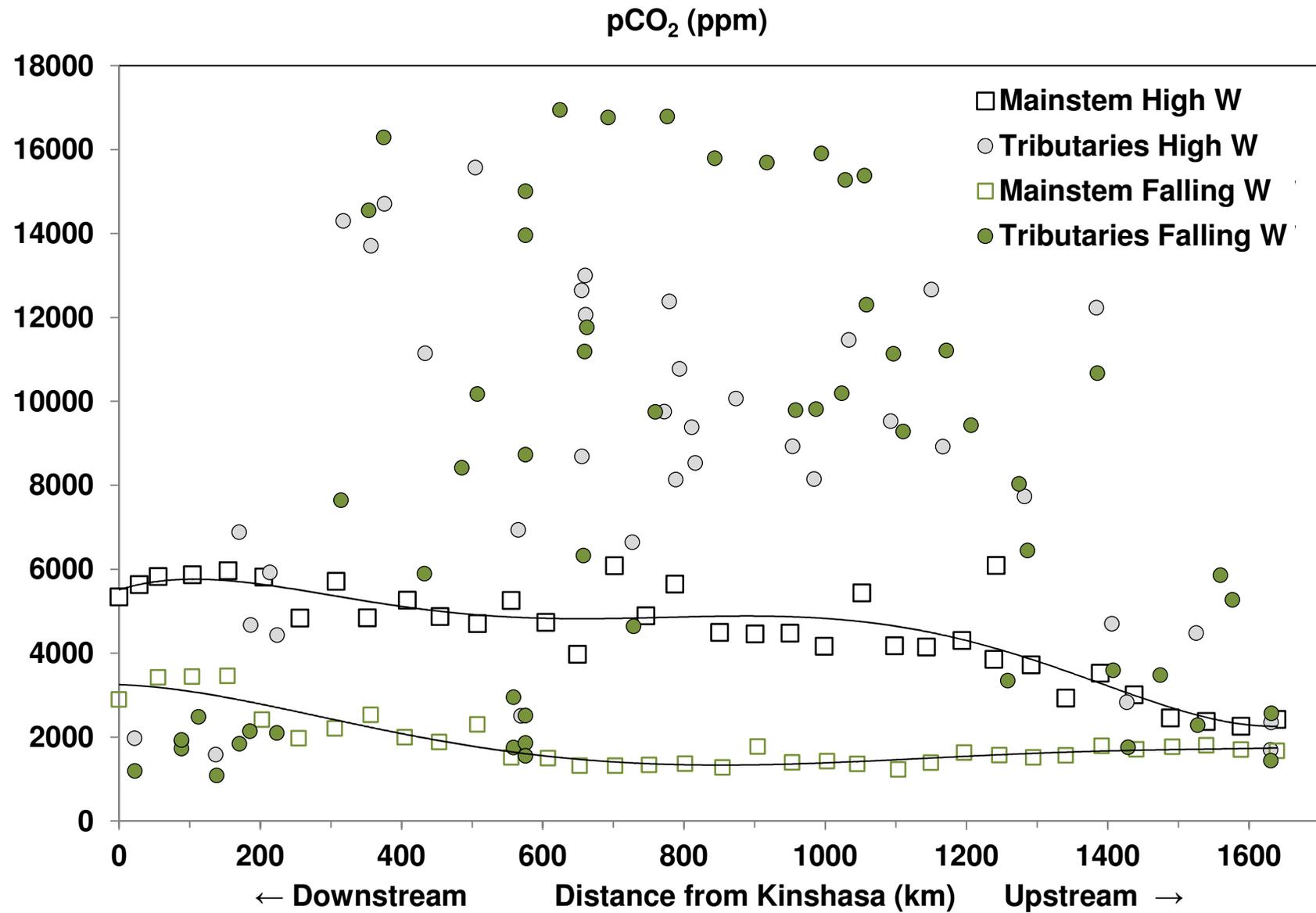
# Results



# Results

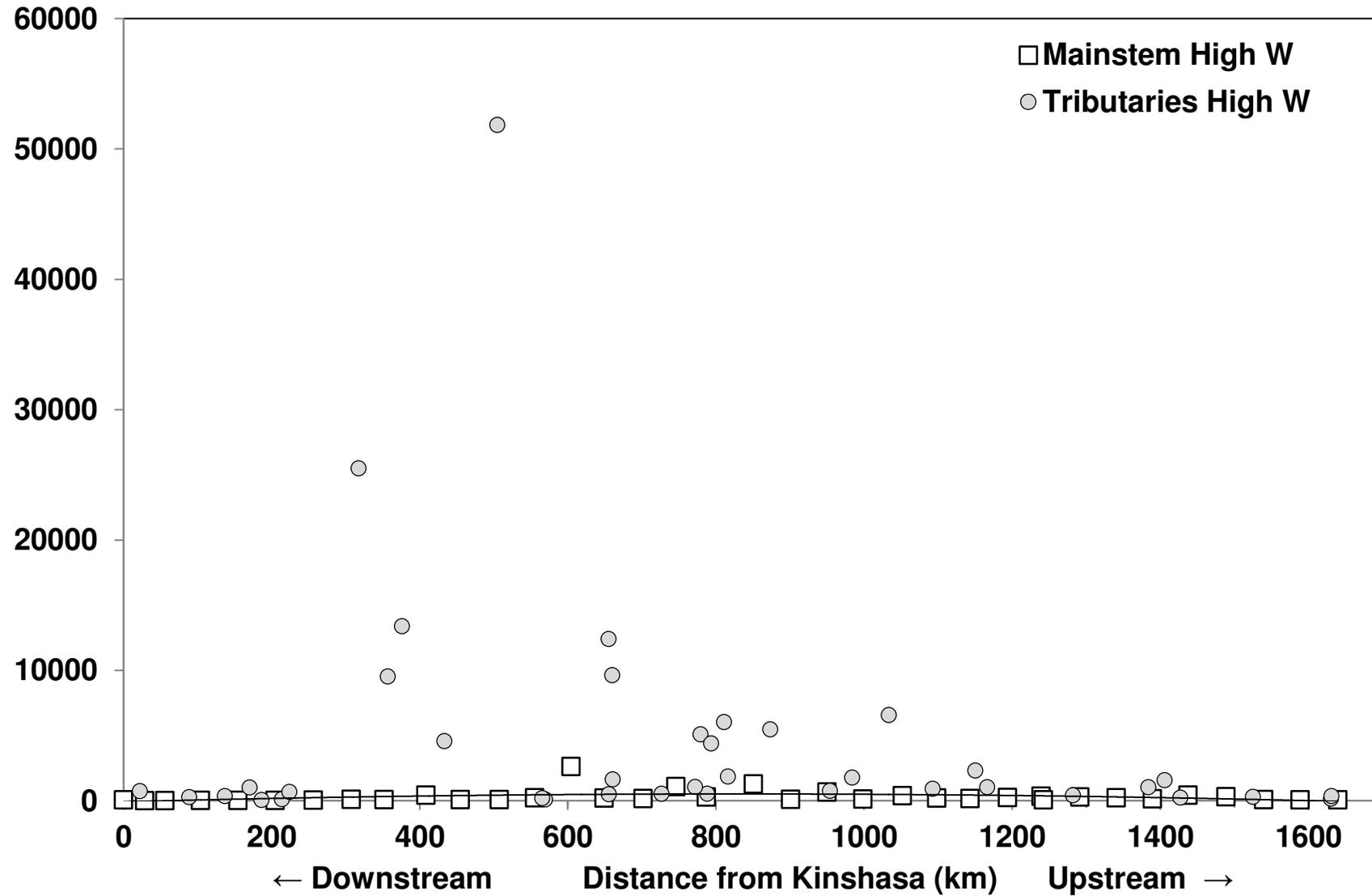


# Results

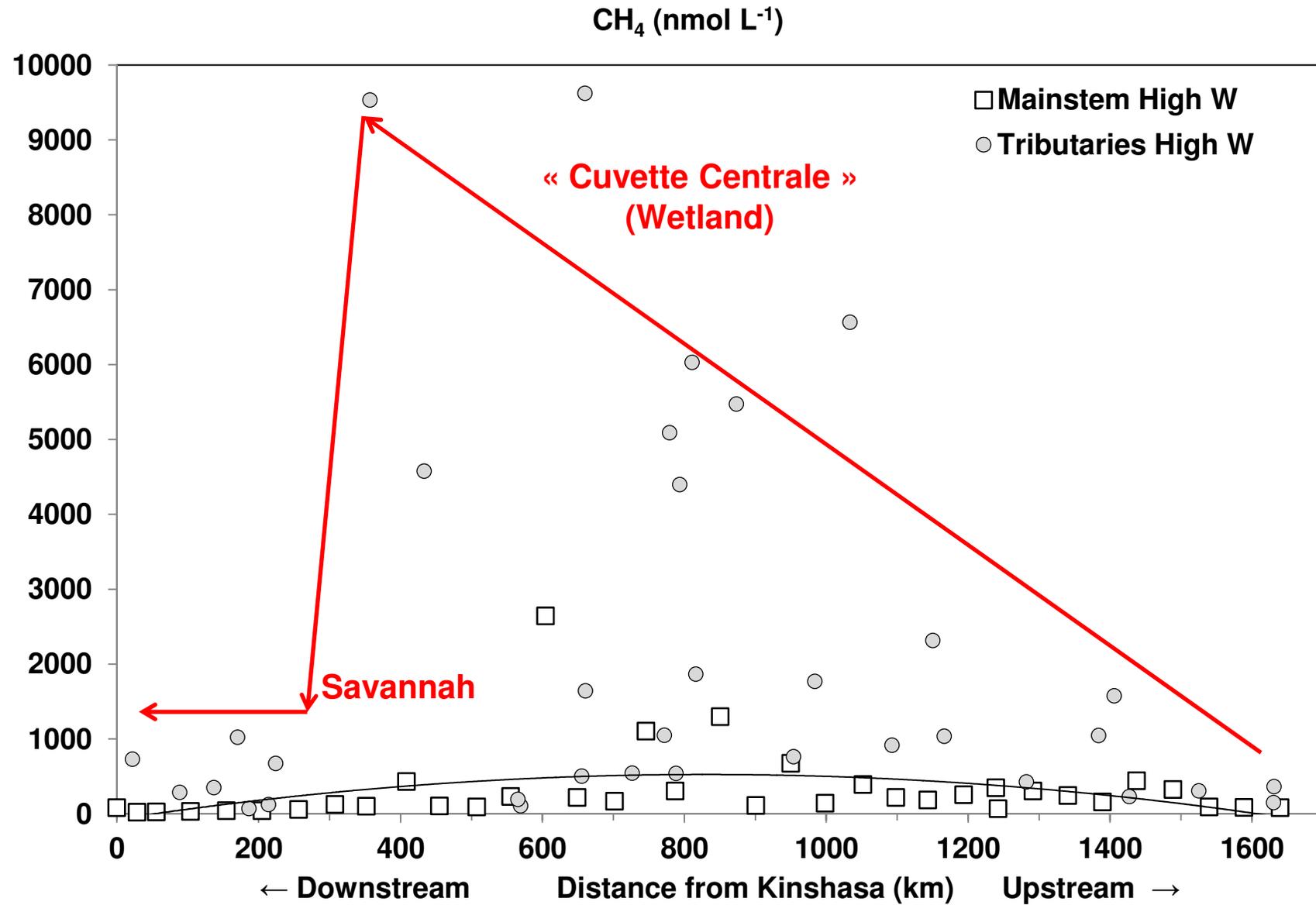


# Results

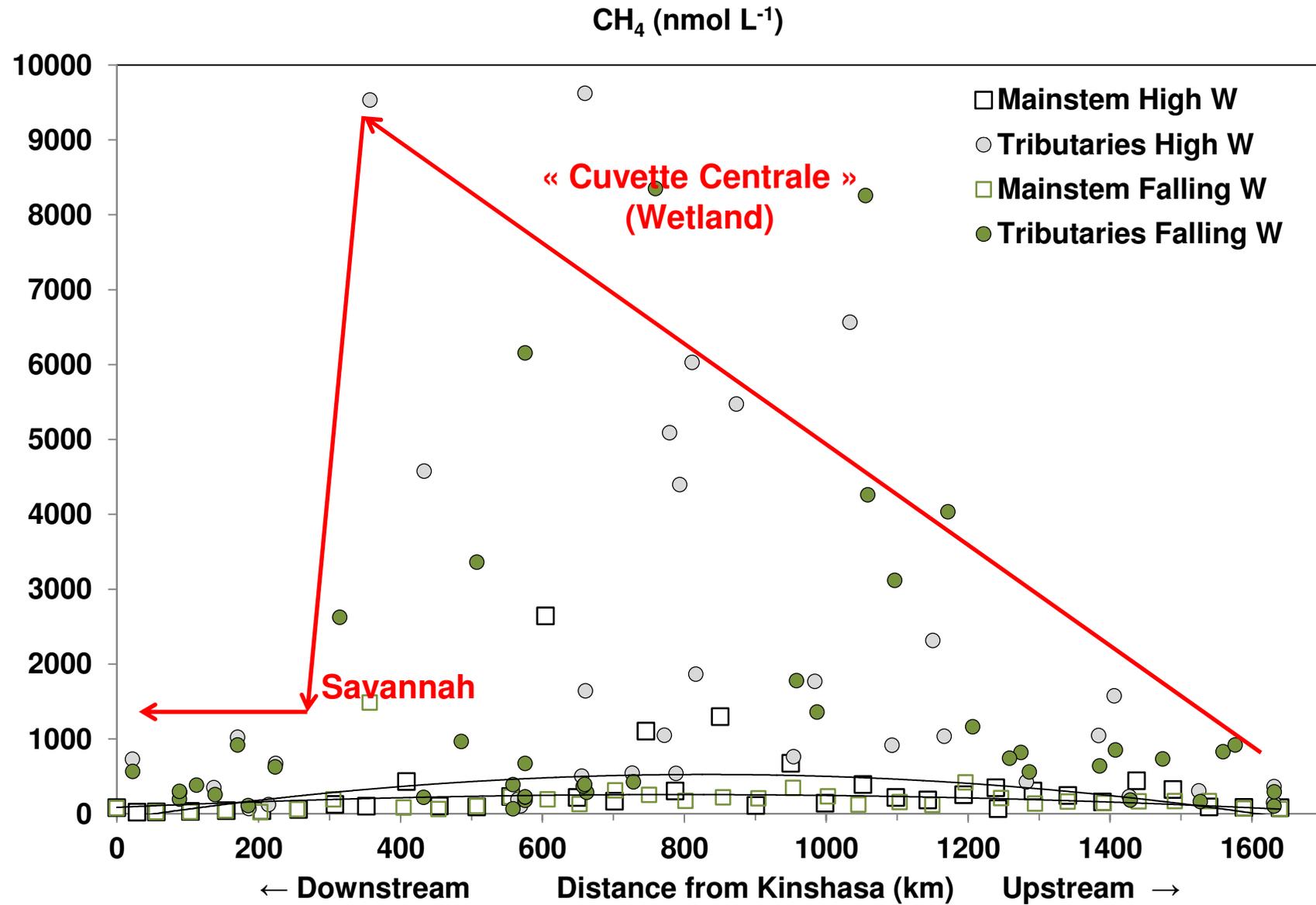
CH<sub>4</sub> (nmol L<sup>-1</sup>)



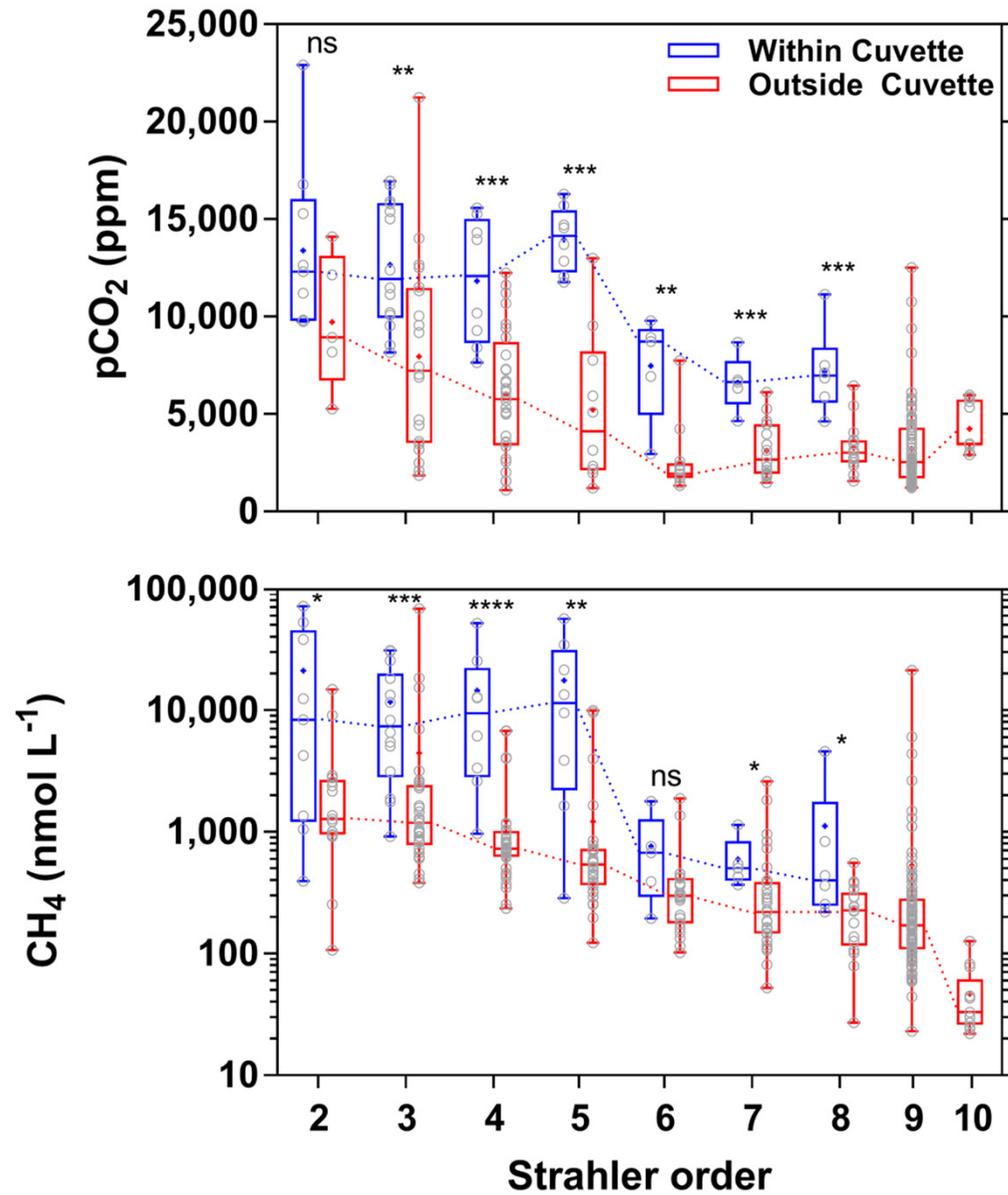
# Results



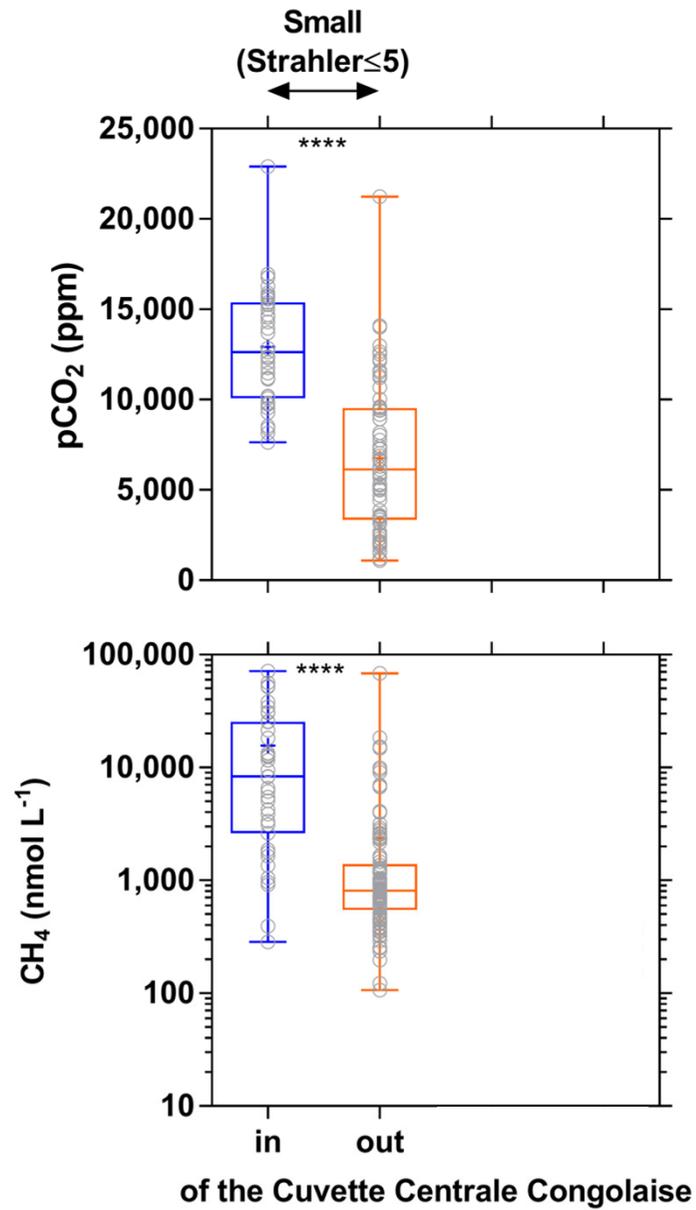
# Results



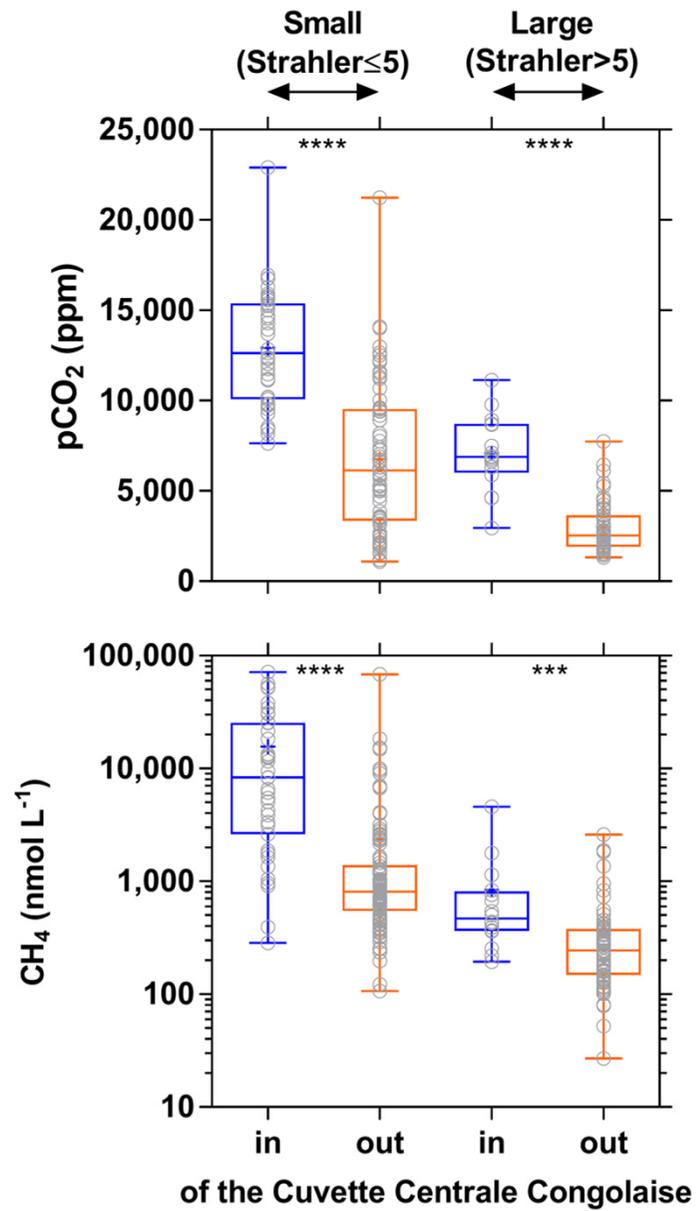
# Results



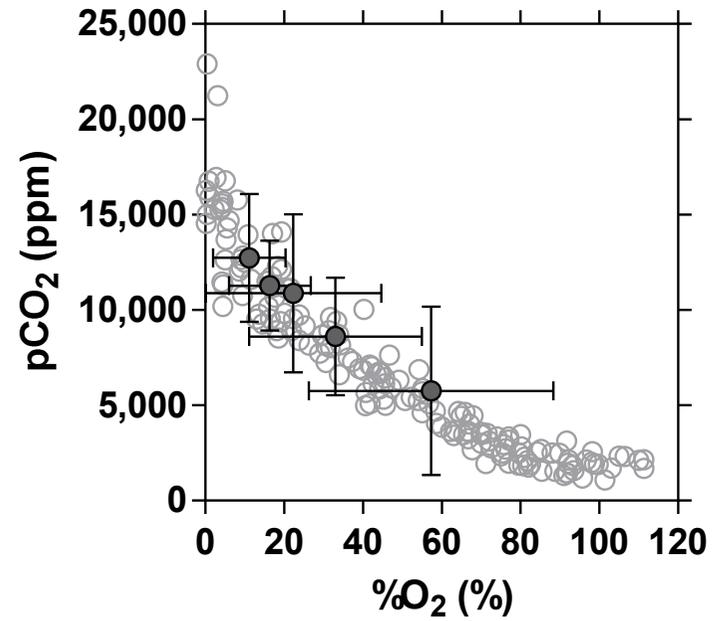
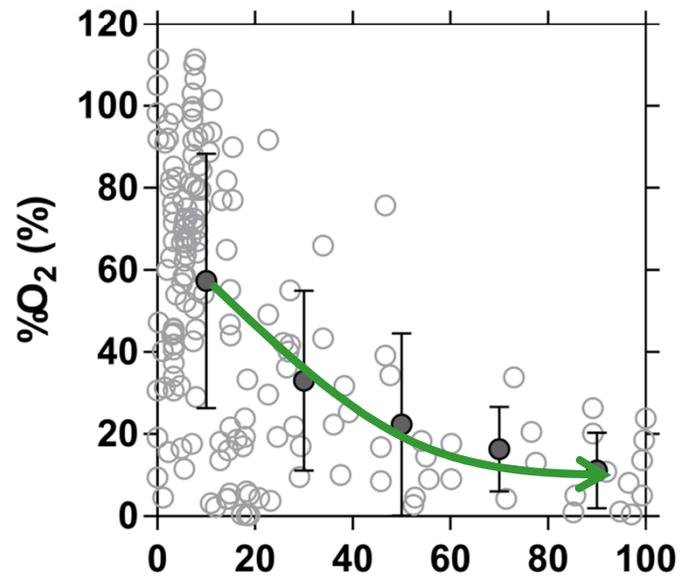
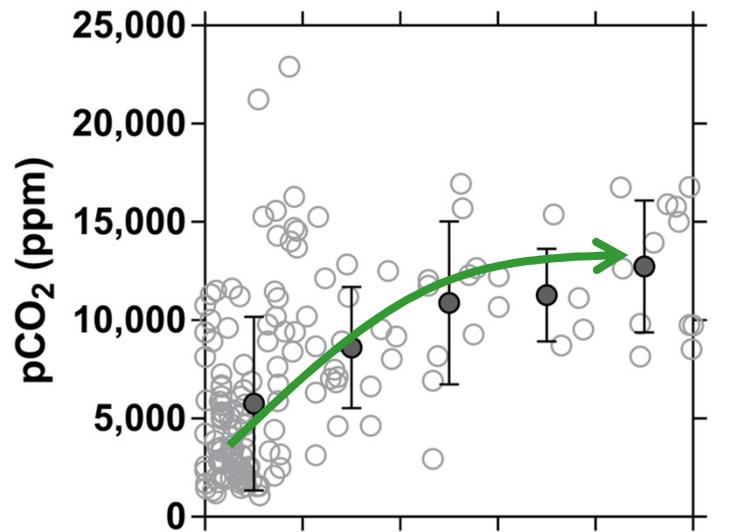
# Results



# Results



# Results

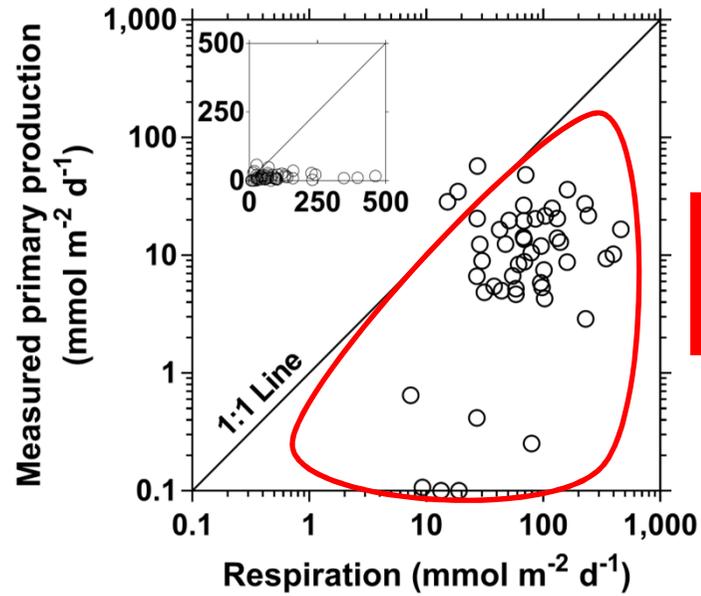


Flooded dense forest on catchment (%)

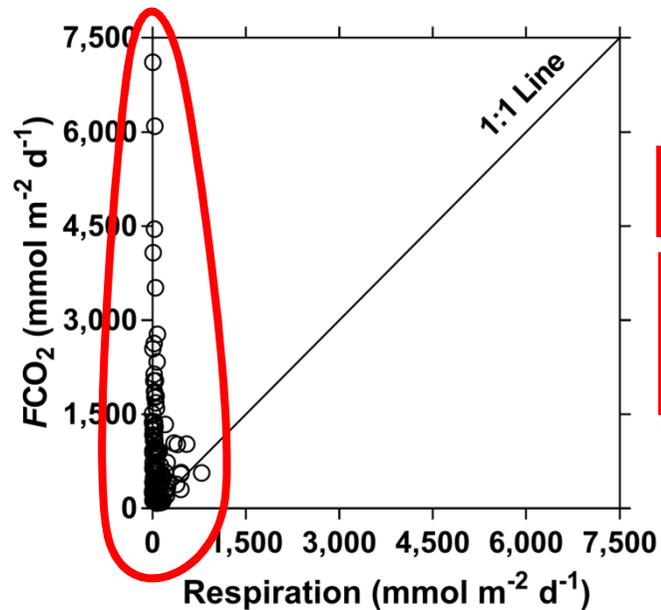
# Results

**Metabolism versus CO<sub>2</sub> emissions**

# Results



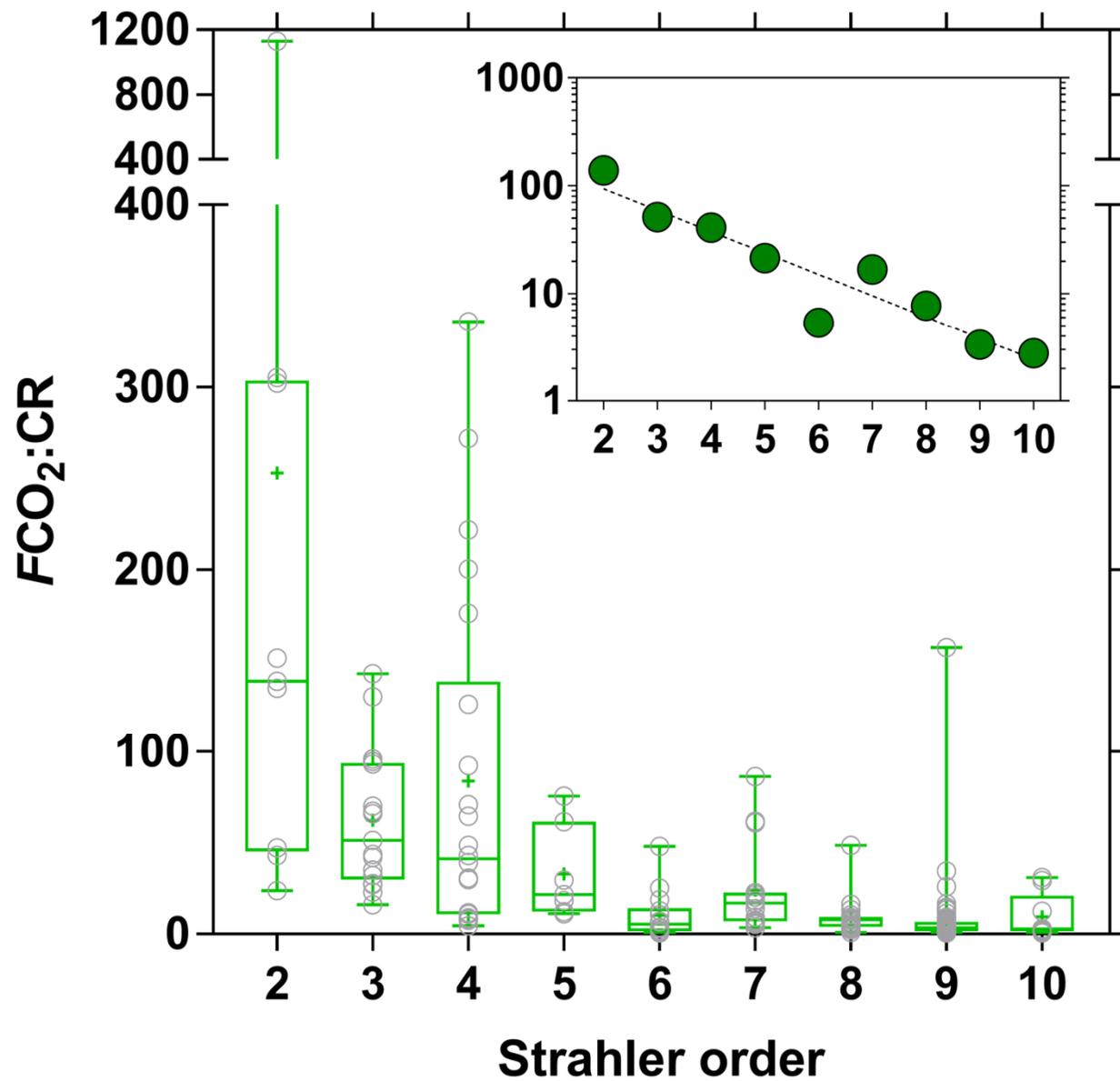
**Net heterotrophic  
R >> P**



**CO<sub>2</sub> emission >> R**

**Lateral CO<sub>2</sub> inputs  
>> in-stream R**

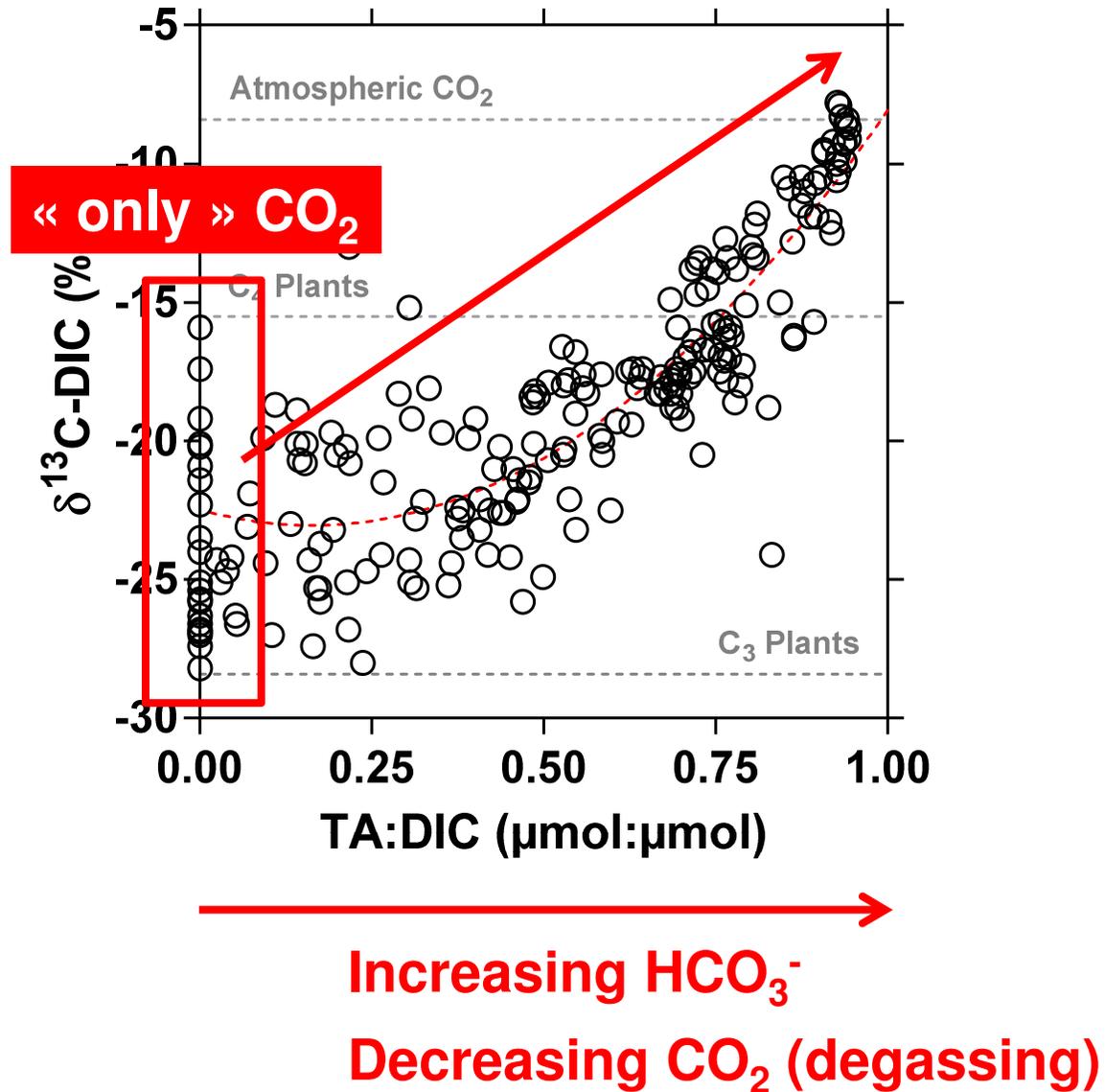
# Results



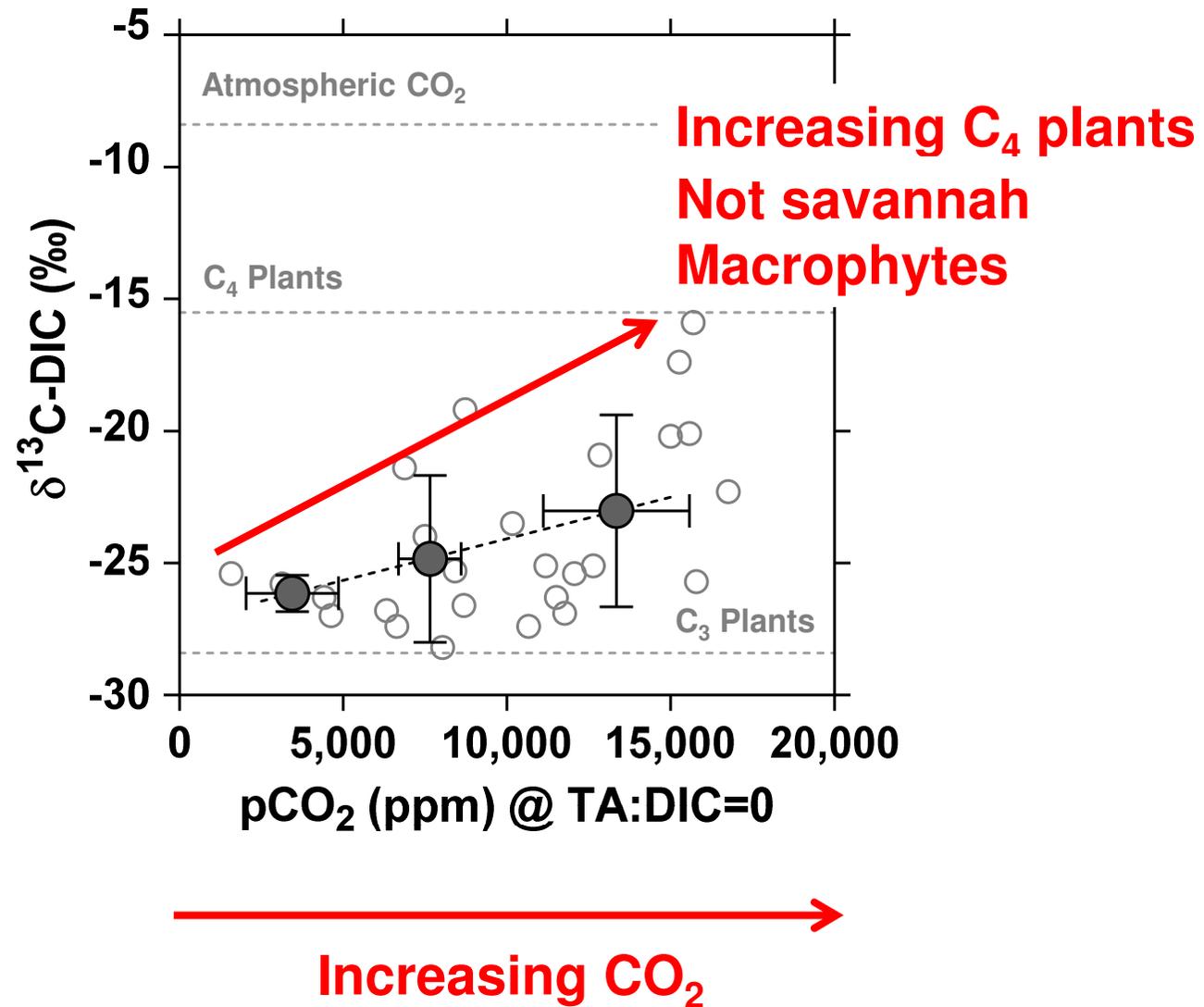
# Results

**Stable isotopic composition of DIC**

# Results



# Results



# Results

**CO<sub>2</sub> and CH<sub>4</sub> in rivers & streams of the Congo seem to be mainly related to wetland inputs**

**Based on:**

- **Spatial patterns (in/out of the Cuvette Centrale)**
- **Metabolic measurements**
- **Stable isotopic composition of DIC**

# Results

## CO<sub>2</sub> emission from Congo rivers-streams

$$FCO_2 = k H \Delta pCO_2$$

$FCO_2$  = air-water CO<sub>2</sub> flux

$H$  = Henry's constant = f(temperature)

$\Delta pCO_2$  = air-water gradient of pCO<sub>2</sub> (measured)

$k$  = gas transfer velocity

$k = f$  (flow velocity; slope)

Limnology and Oceanography

## FLUIDS & ENVIRONMENTS

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ORIGINAL ARTICLE

### Scaling the gas transfer velocity and hydraulic geometry in streams and small rivers

Peter A. Raymond,<sup>1</sup> Christopher J. Zappa,<sup>2</sup> David Butman,<sup>1</sup> Thomas L. Bott,<sup>3</sup> Jody Potter,<sup>4</sup> Patrick Mulholland,<sup>5</sup> Andrew E. Laursen,<sup>6</sup> William H. McDowell,<sup>4</sup> and Denis Newbold<sup>3</sup>

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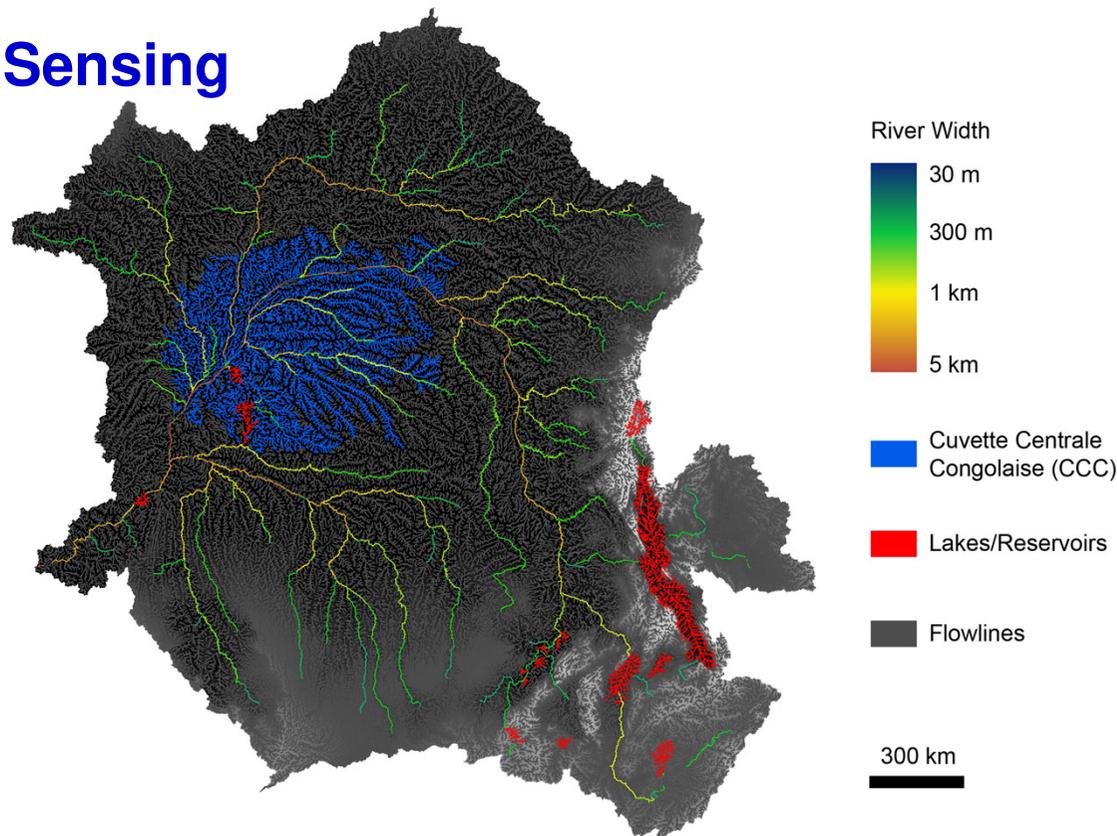
# Results

**CO<sub>2</sub> emission from Congo rivers-streams**

**Stream surface area = length x width**

**length = Hydrosheds**

**width = Remote Sensing**



Science

**Global extent of rivers and streams**

George H. Allen\*† and Tamlin M. Pavelsky

# Results

**CO<sub>2</sub> emission from Congo rivers-streams  
= 251 TgC yr<sup>-1</sup>**

**Net ecosystem exchange (NEE) Congo forests + savannahs  
= 77 TgC yr<sup>-1</sup>**

???

**Export of C from soils to rivers  
= 2-3% of NEE  
for *terra firme* forests**

What ??



Global Change Biology

Global Change Biology (2011) 17, 1167–1185, doi: 10.1111/j.1365-2486.2010.02282.x

## Dissolved carbon leaching from soil is a crucial component of the net ecosystem carbon balance

REIMO KINDLER\*<sup>1,2</sup>, JAN SIEMENS\*<sup>§2,3</sup>, KLAUS KAISER<sup>†</sup>, DAVID C. WALMSLEY<sup>‡</sup>, CHRISTIAN BERNHOFER<sup>§</sup>, NINA BUCHMANN<sup>¶</sup>, PIERRE CELLIER<sup>||</sup>, WERNER EUGSTER<sup>¶</sup>, GERD GLEIXNER\*\*<sup>††</sup>, THOMAS GRÜNWARD<sup>§</sup>, ALEXANDER HEIM<sup>††</sup>, ANDREAS IBROM<sup>‡‡</sup>, STEPHANIE K. JONES<sup>§§</sup>, MIKE JONES<sup>¶¶</sup>, KATJA KLUMPP<sup>|||</sup>, WERNER KUTSCH\*\*\*<sup>†††</sup>, KLAUS STEENBERG LARSEN<sup>‡‡</sup>, SIMON LEHUGER<sup>||</sup>, BENJAMIN LOUBET<sup>||</sup>, REBECCA MCKENZIE<sup>†††</sup>, EDDY MOORS<sup>‡‡‡</sup>, BRUCE OSBORNE<sup>‡</sup>, KIM PILEGAARD<sup>‡‡</sup>, CORINNA REBMANN<sup>§§§</sup>, MATTHEW SAUNDERS<sup>‡</sup>, MICHAEL W. I. SCHMIDT<sup>†††</sup>, MARION SCHRUMPF\*\*<sup>††</sup>, JANINE SEYFFERTH\*\*<sup>††</sup>, UTE SKIBA<sup>§§</sup>, JEAN-FRANCOIS SOUSSANA<sup>|||</sup>, MARK A. SUTTON<sup>§§</sup>, CINDY TEFS\*\*<sup>††</sup>, BERNHARD VOWINCKEL<sup>§</sup>, MATTHIAS J. ZEEMAN<sup>¶</sup> and MARTIN KAUPENJOHANN\*

## Results

**CO<sub>2</sub> emission from Congo rivers-streams  
= 251 TgC yr<sup>-1</sup>**

**Mostly sustained by C leaked from wetlands ?**

**Export C from flooded forest in Amazon (Abril et al.)**

**+**

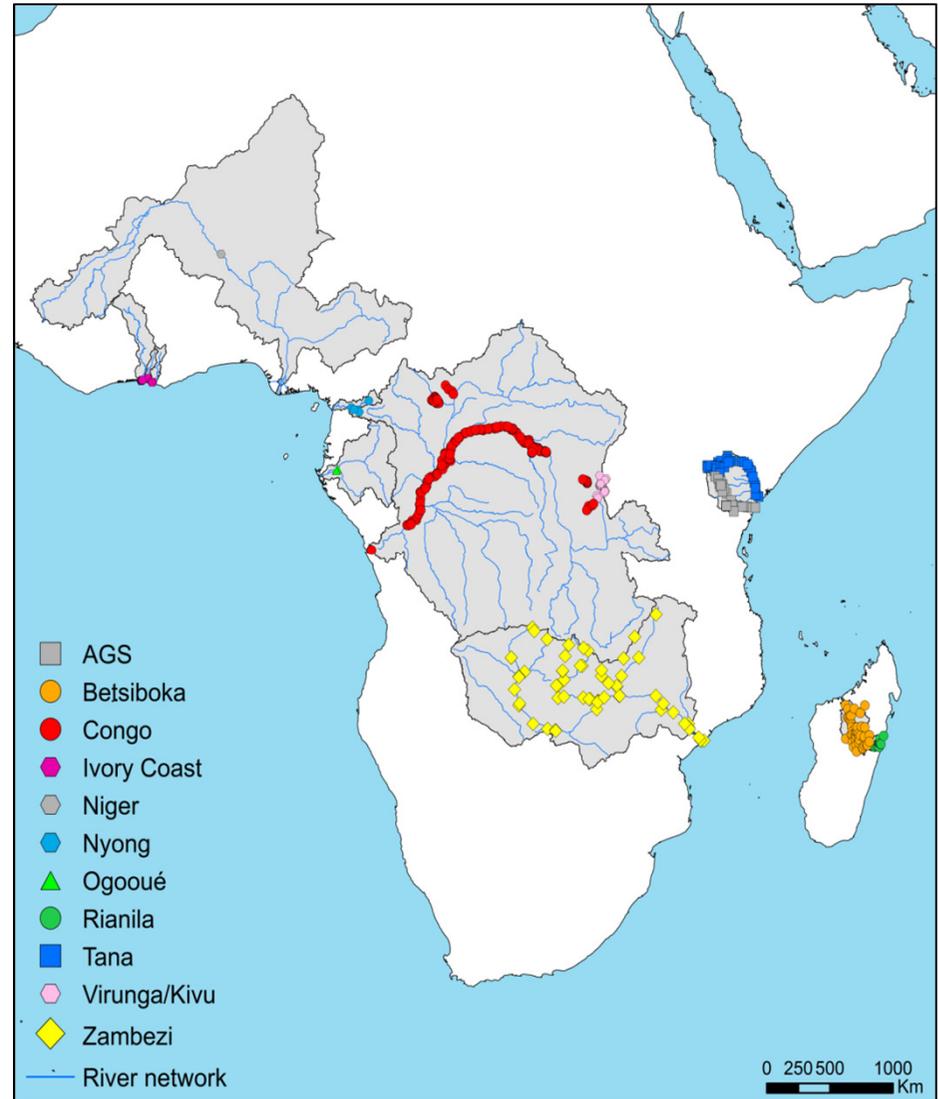
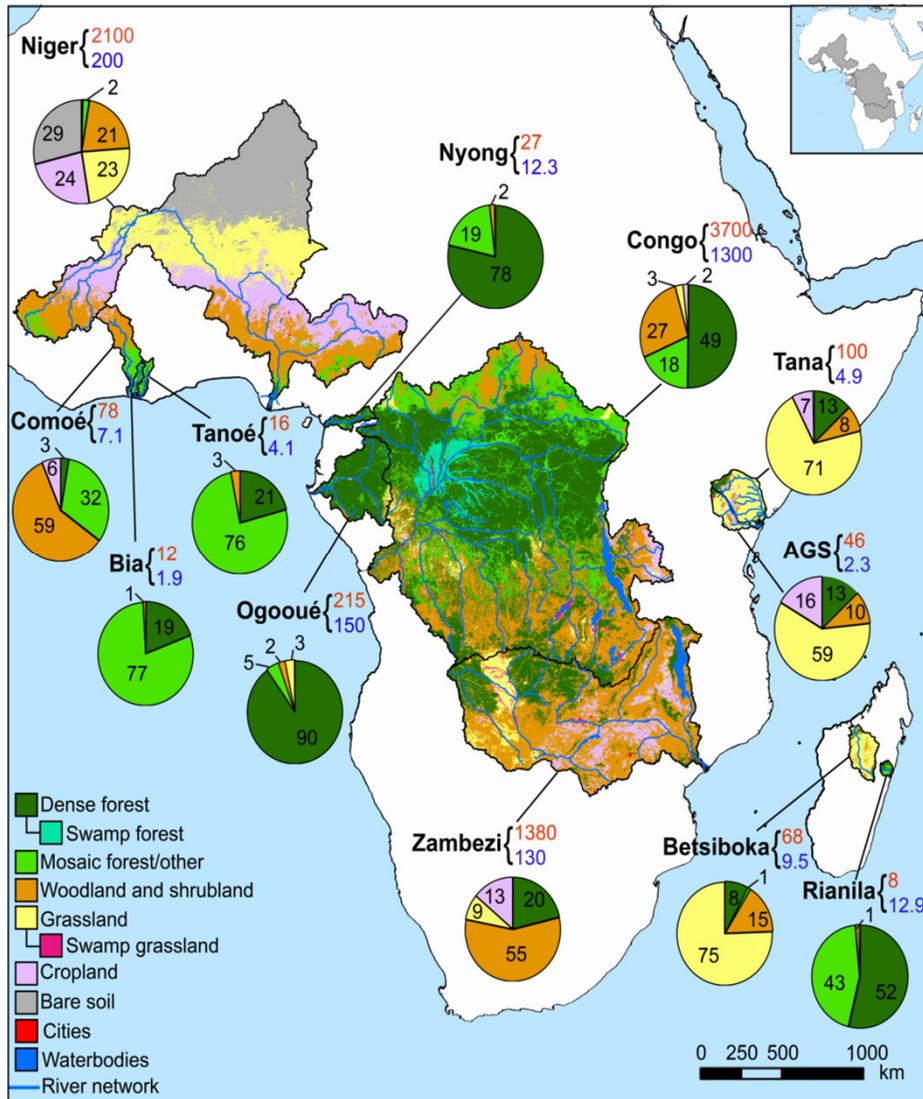
**Surface of flooded forest in Congo  
= 400 TgC yr<sup>-1</sup>**



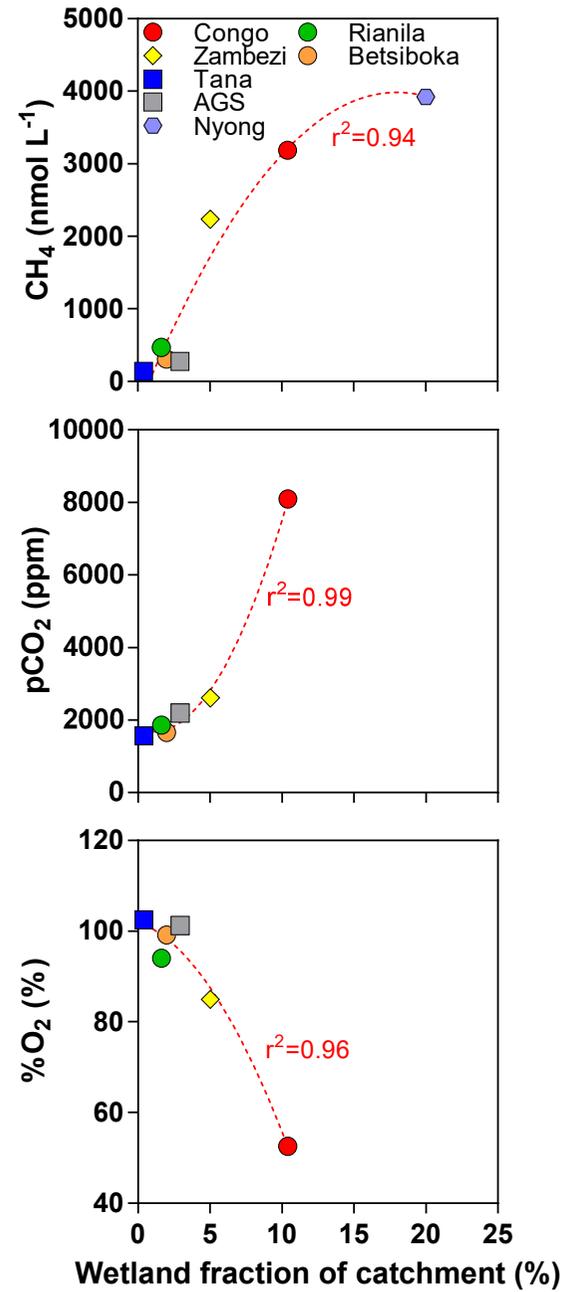
# Results

**Congo & other African rivers**

# Results



# Results



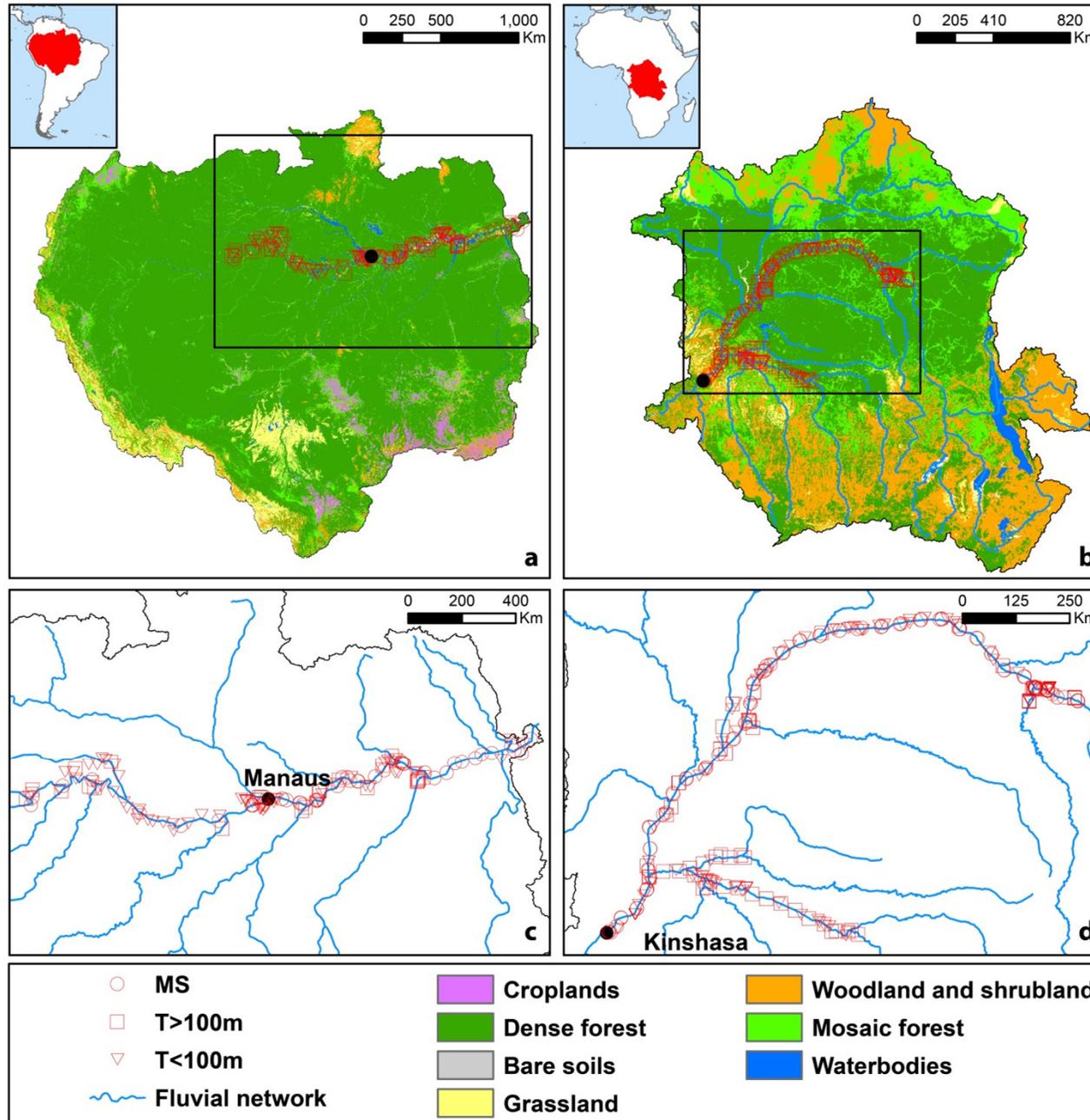
# Results

**Congo versus Amazon**

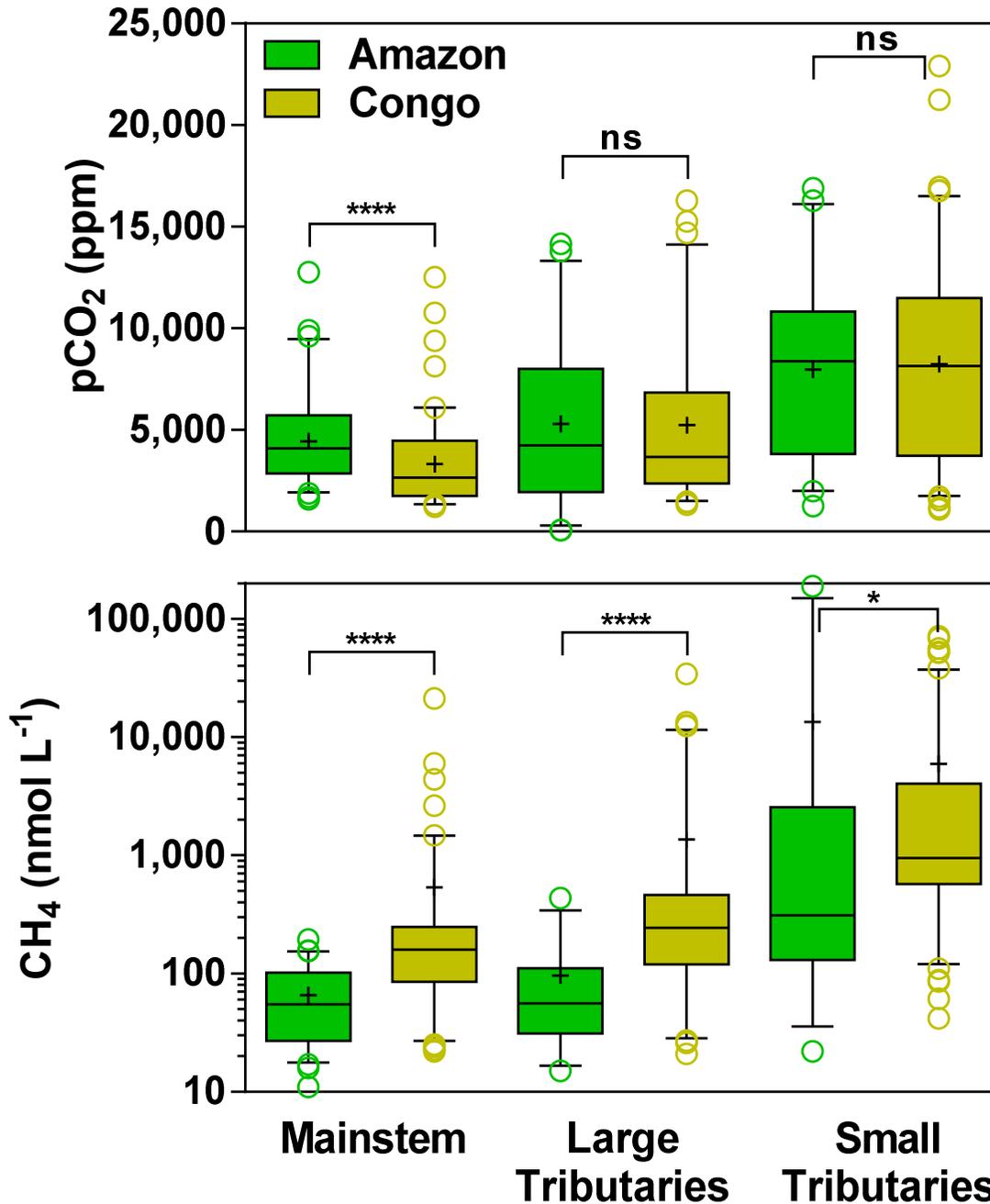
## Results

	Amazon		Congo
Catchment area (km <sup>2</sup> )	6,025,735	>	3,705,222
Slope (°)	1.4		0.6
Discharge (km <sup>3</sup> yr <sup>-1</sup> )	5,444		1,270
Specific discharge (L s <sup>-1</sup> km <sup>-2</sup> )	29	>	11
Precipitation (mm)	2,147	>	1,527
Air temperature (°C)	24.6		23.7
River-stream surface area (km <sup>2</sup> )	74,904		26,517
Wetland surface area (%)	14		10
Above ground biomass (Mg km <sup>-2</sup> )	909	>	748
Land cover			
Dense Forest (%)	83	>	49
Mosaic Forest (%)	4		18
Woodland and shrubland (%)	4	<	27
Grassland (%)	5		3
Cropland/Bare soil (%)	4		2

# Results



# Results

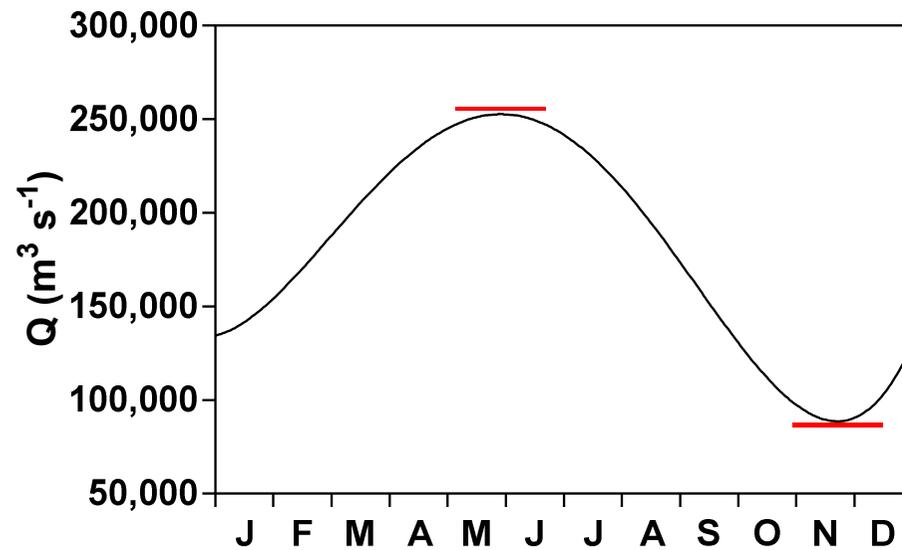


pCO<sub>2</sub> is ± similar

CH<sub>4</sub> is 3-4 times higher in Congo

# Results

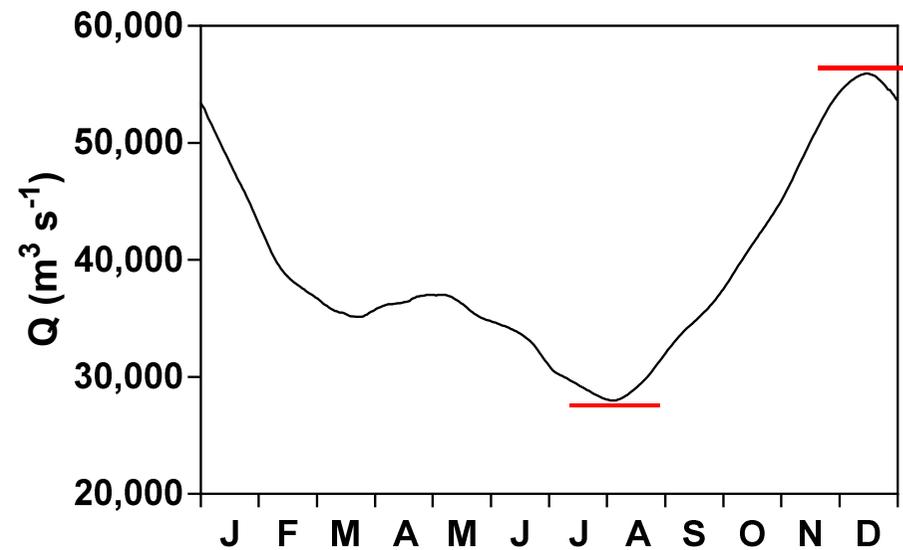
## Amazon



$$Q_{\max} : Q_{\min} = 2.85$$

$$H_{\max} - H_{\min} = 10-12 \text{ m}$$

## Congo



$$Q_{\max} : Q_{\min} = 1.99$$

$$H_{\max} - H_{\min} = 3-4 \text{ m}$$

# Further Reading

Biogeosciences, 16, 3801–3834, 2019

<https://doi.org/10.5194/bg-16-3801-2019>

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## **Variations in dissolved greenhouse gases (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) in the Congo River network overwhelmingly driven by fluvial-wetland connectivity**

Alberto V. Borges<sup>1</sup>, François Darchambeau<sup>1,a</sup>, Thibault Lambert<sup>1,b</sup>, Cédric Morana<sup>2</sup>, George H. Allen<sup>3</sup>, Ernest Tambwe<sup>4</sup>, Alfred Toengaho Sembaito<sup>4</sup>, Taylor Mambo<sup>4</sup>, José Nlandu Wabakhangazi<sup>5</sup>, Jean-Pierre Descy<sup>1</sup>, Cristian R. Teodoru<sup>2,c</sup>, and Steven Bouillon<sup>2</sup>

## Further Reading

nature  
geoscience

ARTICLES

PUBLISHED ONLINE: 20 JULY 2015 | DOI: 10.1038/NGEO2486

### Globally significant greenhouse-gas emissions from African inland waters

Alberto V. Borges<sup>1\*</sup>, François Darchambeau<sup>1</sup>, Cristian R. Teodoru<sup>2</sup>, Trent R. Marwick<sup>2</sup>, Fredrick Tamooh<sup>2,3</sup>, Naomi Geeraert<sup>2</sup>, Fredrick O. Omengo<sup>2</sup>, Frédéric Guérin<sup>4</sup>, Thibault Lambert<sup>1</sup>, Cédric Morana<sup>2</sup>, Eric Okuku<sup>2,5</sup> and Steven Bouillon<sup>2</sup>

SCIENTIFIC REPORTS 

OPEN

### Divergent biophysical controls of aquatic CO<sub>2</sub> and CH<sub>4</sub> in the World's two largest rivers

Received: 07 July 2015

Accepted: 29 September 2015

Published: 23 October 2015

Alberto V. Borges<sup>1</sup>, Gwenaél Abril<sup>2,3</sup>, François Darchambeau<sup>1</sup>, Cristian R. Teodoru<sup>4</sup>, Jonathan Deborde<sup>2</sup>, Luciana O. Vidal<sup>5</sup>, Thibault Lambert<sup>1</sup> & Steven Bouillon<sup>4</sup>

# Acknowledgments



European  
Research  
Council



