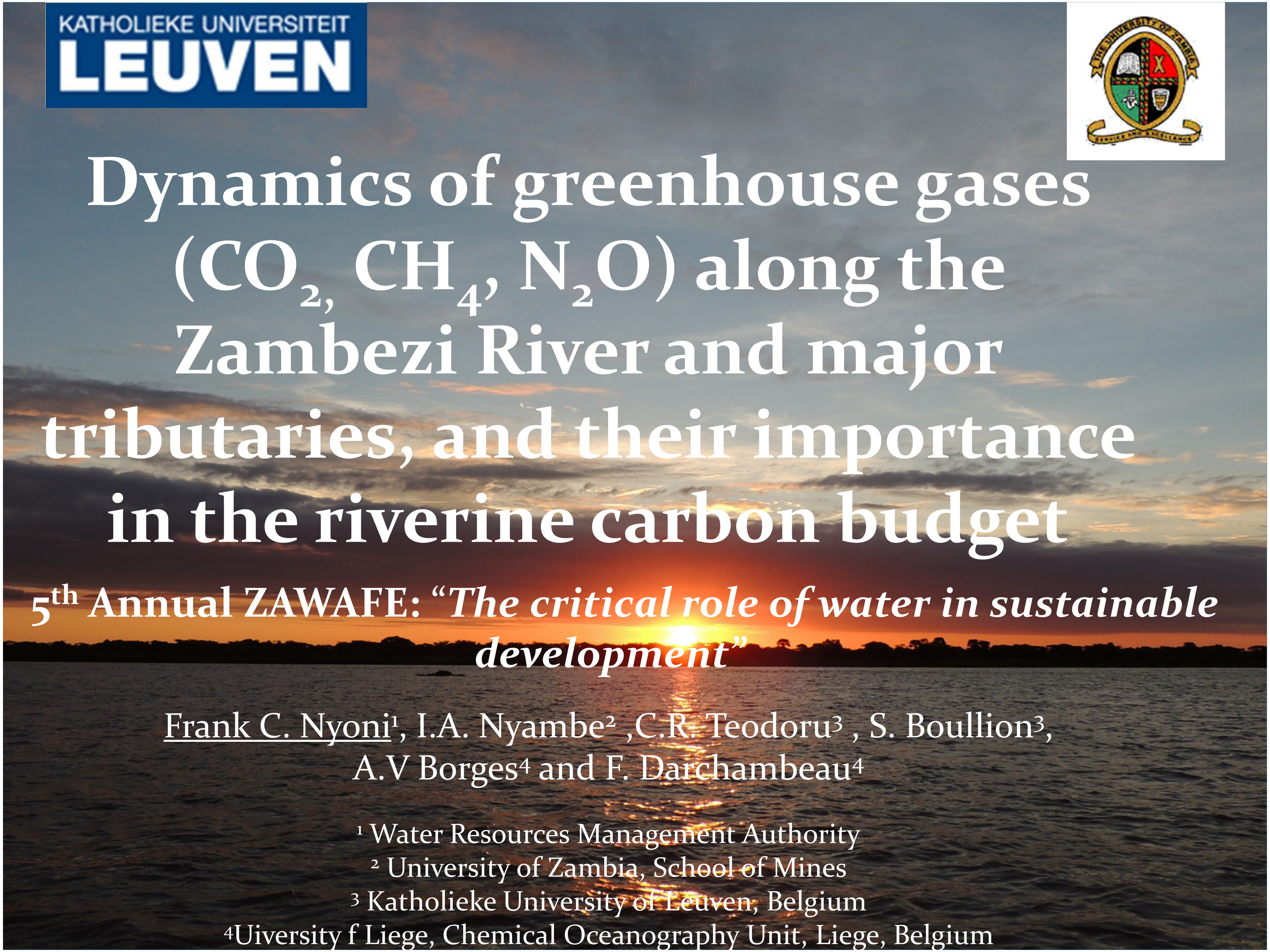

Dynamics of greenhouse gases (CO_2, CH_4, N_2O) along the Zambezi River and major tributaries, and their importance in the riverine carbon budget

5th Annual ZAWAFE: *"The critical role of water in sustainable development"*

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Outline of the Presentation

1.0 Introduction

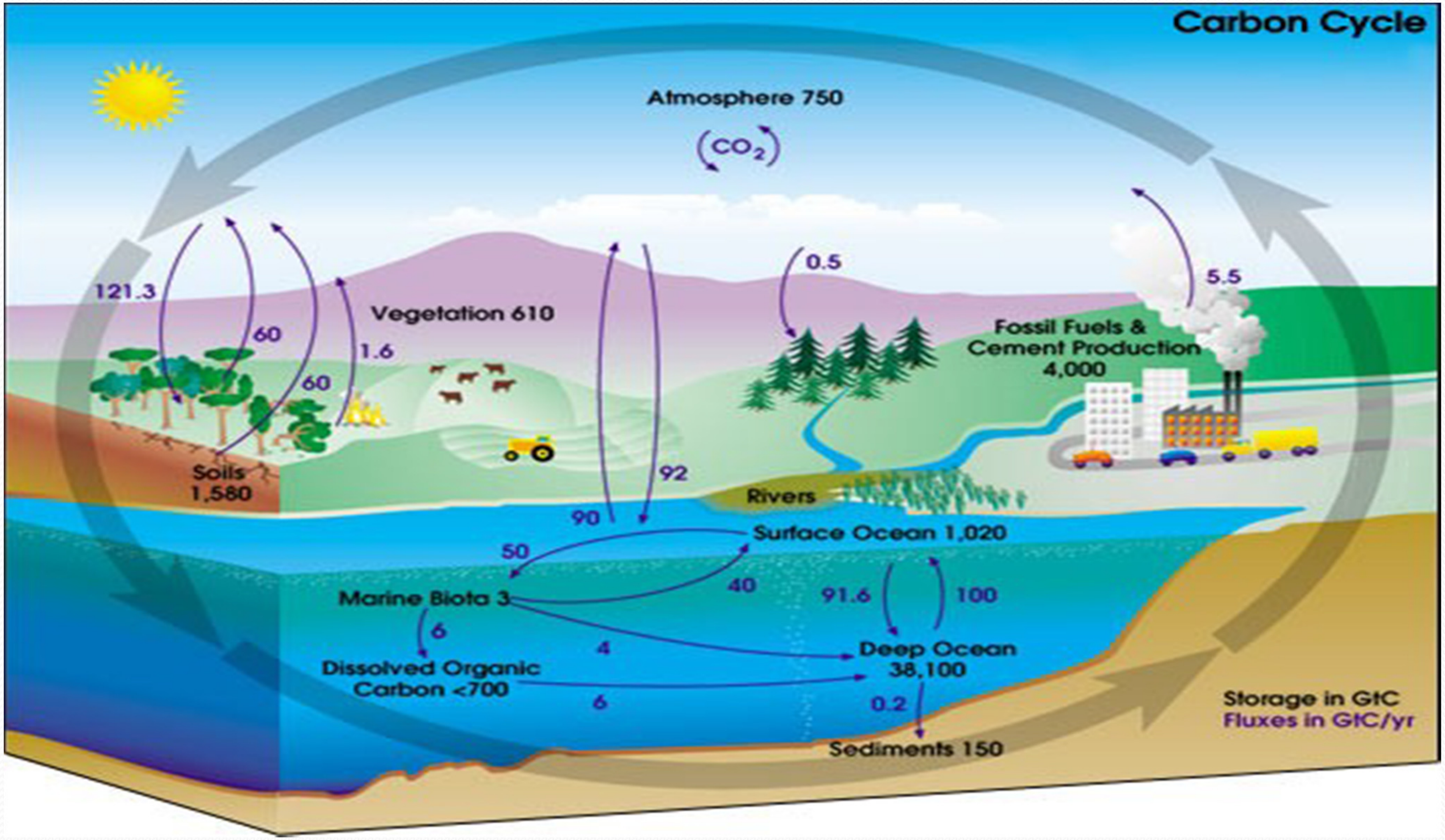
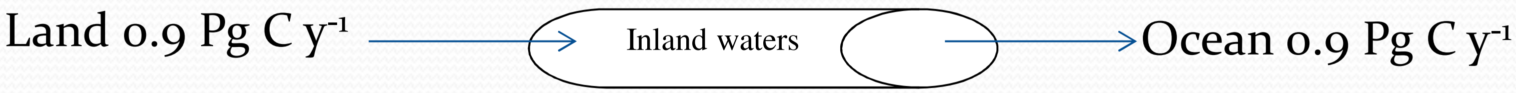


Fig. 1 THE GLOBAL CARBON CYCLE.

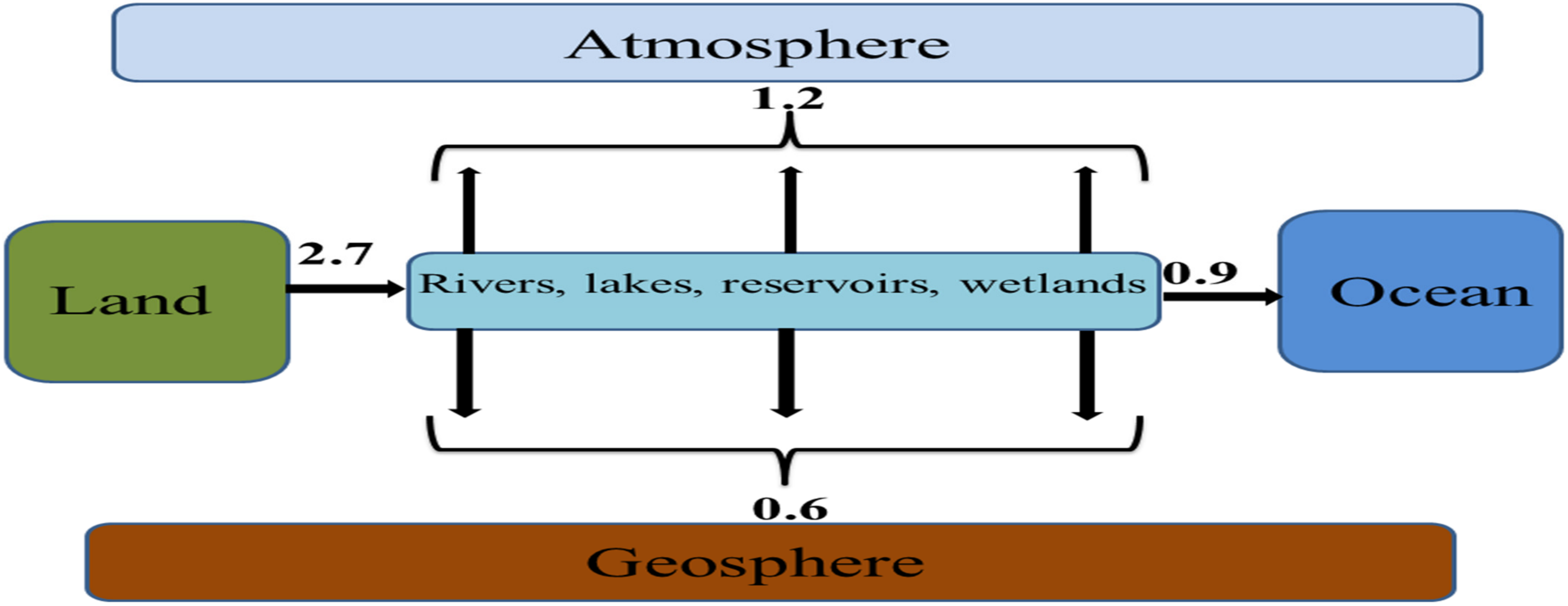
All pools are expressed in units of 10^{15} g C and all annual fluxes (indicated by arrows) in units of 10^{15} g C yr^{-1} (NASA Earth Science Enterprise, 2010)

Earlier perception: Inland waters are passive conduits of Carbon



Land 0.9 Pg C y^{-1} → Inland waters → Ocean 0.9 Pg C y^{-1}

But: Freshwater systems function as biogeochemical "hotspots" for GHG emissions



Aufdenkampe et al. (2011)

Note: All figures in Pg C y^{-1}

- As part of a broader study on catchment-scale biogeochemistry of African Rivers, the present study examines the spatial and temporal dynamics of CO_2, CH_4 and N_2O concentrations and fluxes in the Zambezi River Basin based on three sampling campaigns extended over two climatic seasons (wet 2012, wet 2013 and dry 2013)

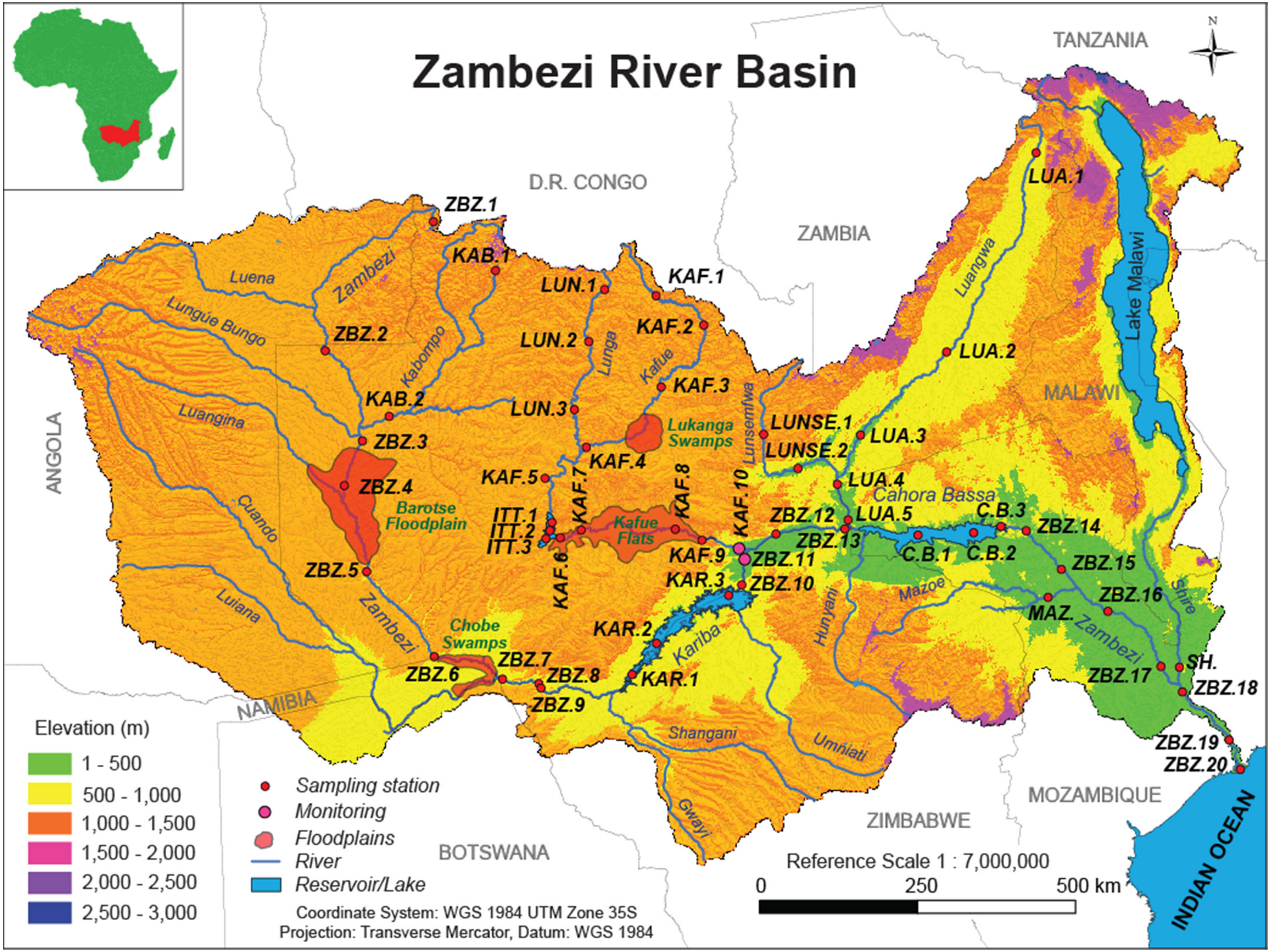
- The study quantifies the magnitude of CO_2 and CH_4 concentrations and fluxes, identifies the main sources and the controlling factors responsible for the observed patterns, and examines hotspots for GHG exchange with atmosphere

- Finally, we make a first attempt at a C mass balance for the Zambezi River over the study period linking emissions, sinks and transport components of the balance to other known elements of C budgets.

2.0 Materials and Methods

General Characteristics

- Zambezi River is the 4th largest river in Africa in terms of discharge after the Congo, Nile and Niger, and the largest flowing into Indian ocean from the African continent
- Almost 75% of the land area in the Zambezi Basin is covered by forest and bush. Cropped land (with mostly rain-fed agriculture) covers up to 13%, and grassland cover about 8% of the land area (SADC, 2012)
- Wetlands, comprising swamps, marshes and seasonally inundated floodplains, are an important component of the basin covering more than 5% of the total basin area (SADC , 2012; McCartney et al., 2013)
- In 1998, the population in the Basin was estimated at 31.7 million (one-third of the total population of the eight basin countries), out of which more than 85% live in Malawi, Zambia and Zimbabwe. Ten years later (2008) the population reached over 40 million and it is predicted to reach 51.2 million by 2025 (SADC, 2012)
- This predicted increase in population, alongside with ongoing economical development in the region and new hydropower projects is expected to exert further pressure on the aquatic environment and natural water resources of the basin.


Zambezi River Basin
TANZANIA
D.R. CONGO
ZAMBIA
ANGOLA
MALAWI
NAMIBIA
BOTSWANA
ZIMBABWE
MOZAMBIQUE
INDIAN OCEAN
N
ZBZ.1
ZBZ.2
ZBZ.3
ZBZ.4
ZBZ.5
ZBZ.6
ZBZ.7
ZBZ.8
ZBZ.9
ZBZ.10
ZBZ.11
ZBZ.12
ZBZ.13
ZBZ.14
ZBZ.15
ZBZ.16
ZBZ.17
ZBZ.18
ZBZ.19
ZBZ.20
KAB.1
KAB.2
LUN.1
LUN.2
LUN.3
KAF.1
KAF.2
KAF.3
KAF.4
KAF.5
KAF.6
KAF.7
KAF.8
KAF.9
KAF.10
ITT.1
ITT.2
ITT.3
KAR.1
KAR.2
KAR.3
LUNSE.1
LUNSE.2
LUA.1
LUA.2
LUA.3
LUA.4
LUA.5
C.B.1
C.B.2
C.B.3
MAZ.
SH.
Luena
Zambezi
Lungúe Bungo
Kabompo
Luangina
Cuando
Luiana
Lunga
Kafue
Lunsemfwa
Luangwa
Lake Malawi
Cahora Bassa
Hunyani
Mazoe
Shire
Kariba
Shangani
Umniati
Gwayi
Barotse Floodplain
Lukanga Swamps
Kafue Flats
Chobe Swamps
Elevation (m)
🟩 1 - 500
🟨 500 - 1,000
🟧 1,000 - 1,500
1,500 - 2,000
🟪 2,000 - 2,500
🟦 2,500 - 3,000
● Sampling station
● Monitoring
Floodplains
River
Reservoir/Lake
Coordinate System: WGS 1984 UTM Zone 35S
Projection: Transverse Mercator, Datum: WGS 1984
Reference Scale 1 : 7,000,000
0
250
500 km

To address the spatial variability, up to 56 sites were visited each campaign, depending on logistics and accessibility

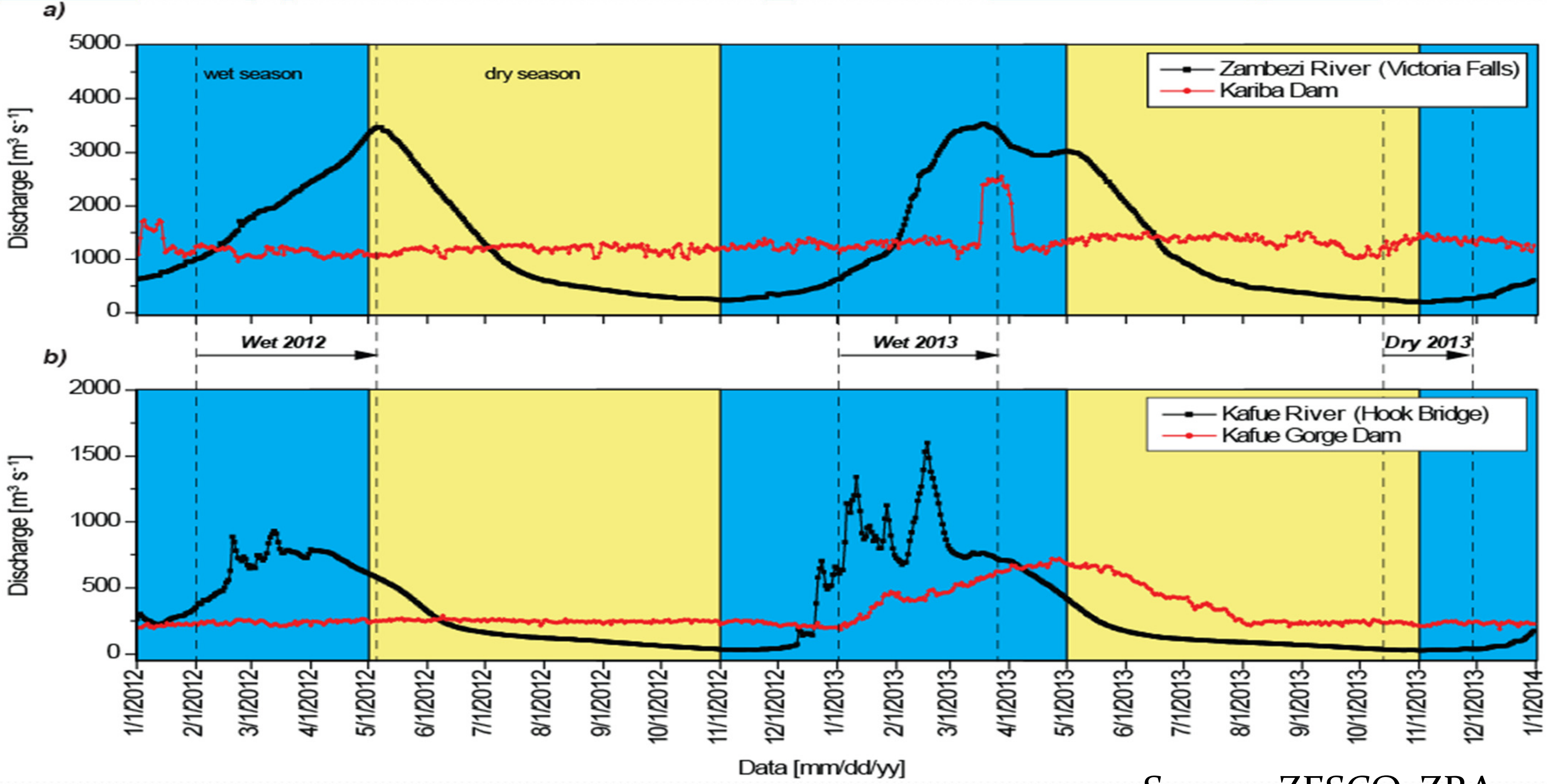
Sampling sites (chosen at 100-150 km apart) were located as follows:

26 along the Zambezi mainstream (including 3 sites on the Kariba and 3 on the Cahora Bassa reservoirs)
13 along the Kafue River (including 3 on the Itezhi Tezhi Reservoir)
2 on the Kabompo River
3 on the Lunga River (main tributary of the Kafue River)
5 along the Luangwa River
2 on the Lunsemfwa River (main tributary of the Luangwa River)
1 on the Mazoe River and 1 on the Shire River

In situ measurements and water sampling was performed, whenever possible, from boats or dugout canoes in the middle of the river at ~0.5 m below the water surface

However, in the absence of boats/canoes, sampling was carried out either from bridges or directly from the shore and as much as possible away from the shoreline in order to avoid any potential contamination.

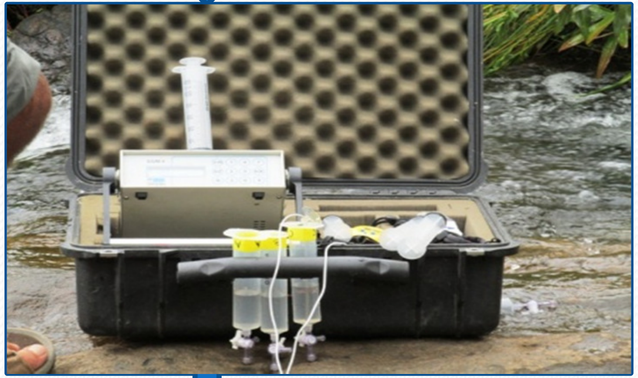
Sampling strategy and analytical technique

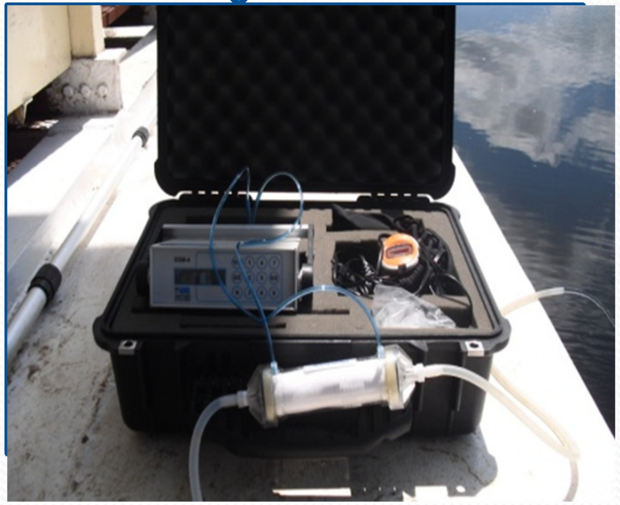


Source: ZESCO, ZRA, 2013

To account for inter-annual variability and seasonality, sampling was conducted during two consecutive years and over two climatic seasons: wet season (1 February to 5 May) 2012, wet season (6 January to 21 March) 2013, and dry season (15 October to 28 November) 2013

pCO_2





Dissolved CH_4 , N2O

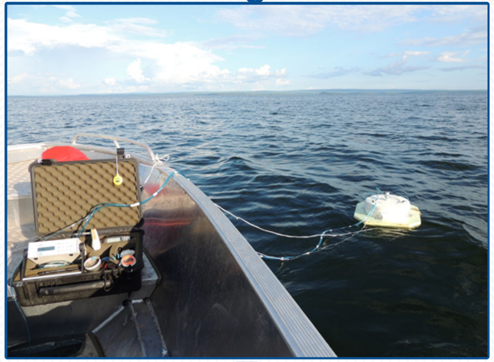
For dissolved CH_4, N_2O;

-Samples were collected in 50ml serum bottles

-Preversed with $HgCl_2$, capped without headspace

Measured by GC (Weiss 1981) with flame ionization detection (GC-FID) and electron capture detection (GC-ECD) with a SRI 8610C GC-FID-ECD calibrated with CH_4:CO_2:N_2O:N_2 mixtures (Air Liquide Belgium) of 1, 10 and 30 ppm CH_4 and of 0.2, 2.0 and 6.0 ppm N_2O, and using the solubility coefficients of Yamamoto et al. (1976) for CH_4 and Weiss and Price (1980) for N_2O

Fluxes for all gases (CO_2, CH_4, N_2O)



For CH_4 and N_2O fluxes;

-60-mL syringe, fitted on a third tube with a two-way valve was filled with 30 mL air from inside the chamber at 0, 5, 10, 20 and 30 minutes interval

-Transferred immediately into a 50-mL septa vial, pre-filled with saturated saline solution

-Samples were stored in upside-down position until analyzed by GC

$$F = [(s \times V)/(mV \times S)] \times f$$

3.0 Results and Discussion

Whereas this work has results on the following;

pH, DO, Temp, SpC, Cond., BR, PP ,TSM, POC, DOC, DIC, TA

Isotopic signatures: $^{13}\delta$-C-DOC, $^{13}\delta$-C-POC, $^{13}\delta$-C-DIC

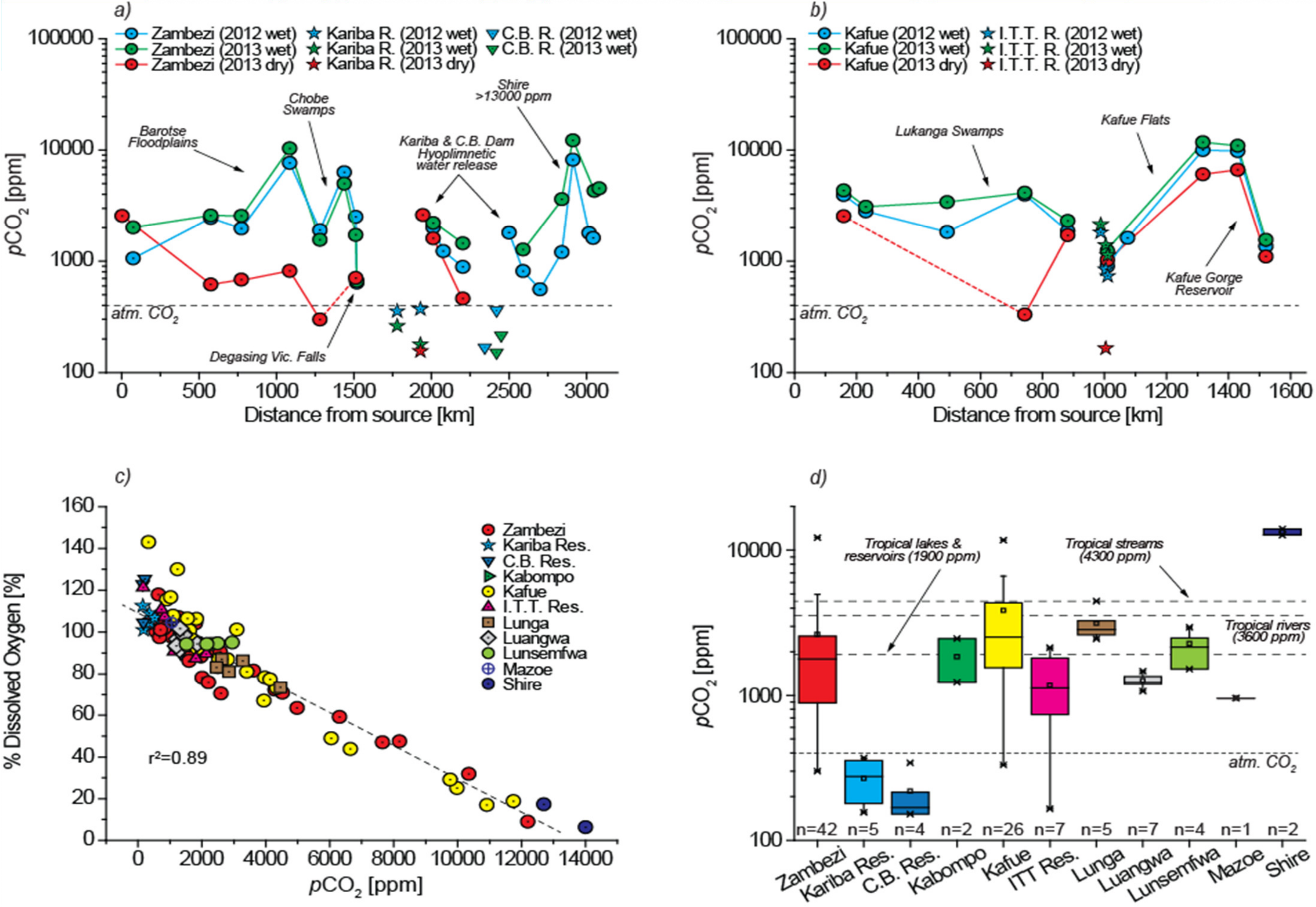
C3, C4 Vegetation classification from the Basin

Nutrients (C, N, P)

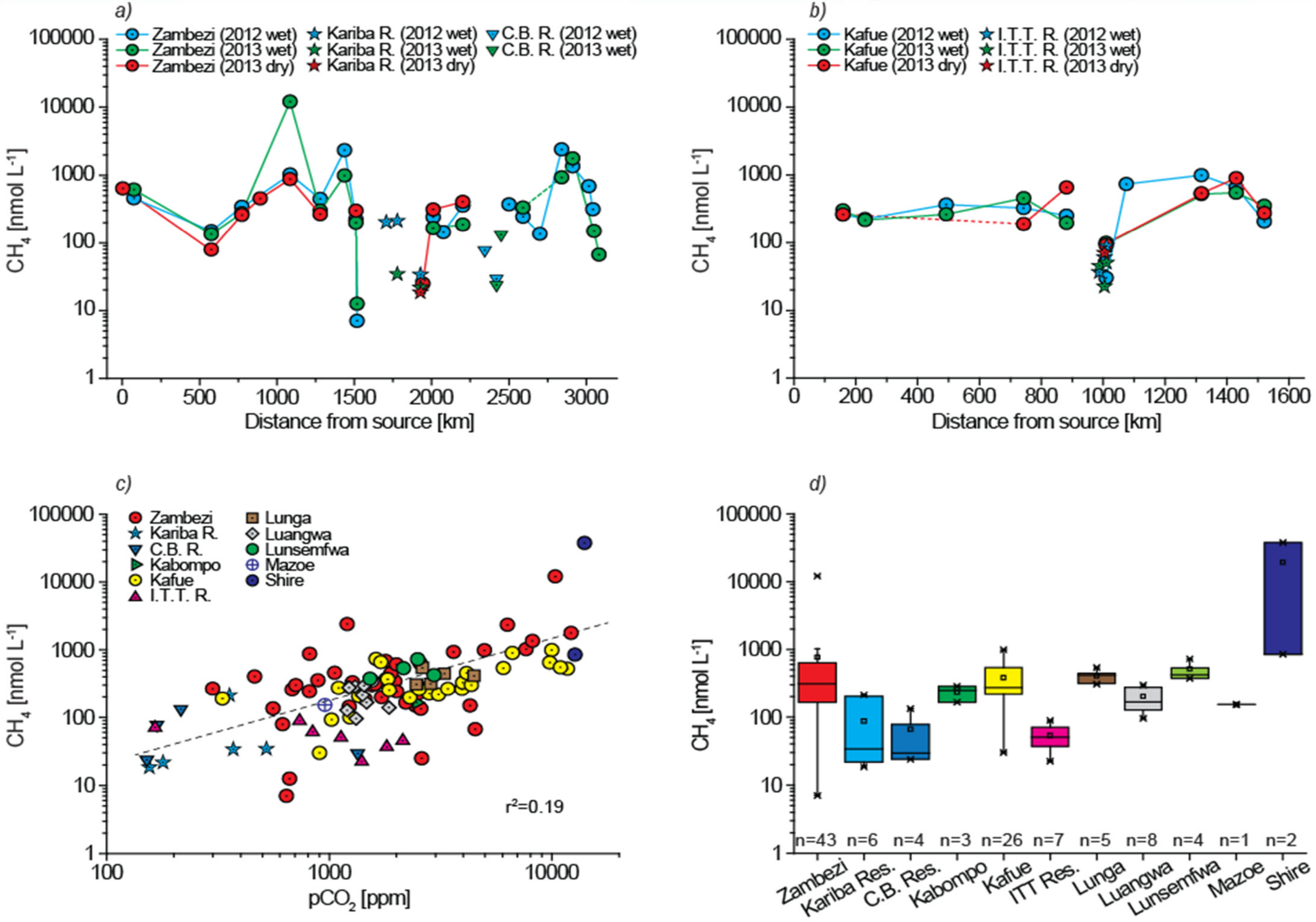
Elements (Ba, Fe, K, Na, Ca, Mg, Zn, SO_3, SiO_2 ,)

We present only data on greenhouse gases (carbon dioxide CO_2, methane CH_4, and nitrous oxide N_2O)

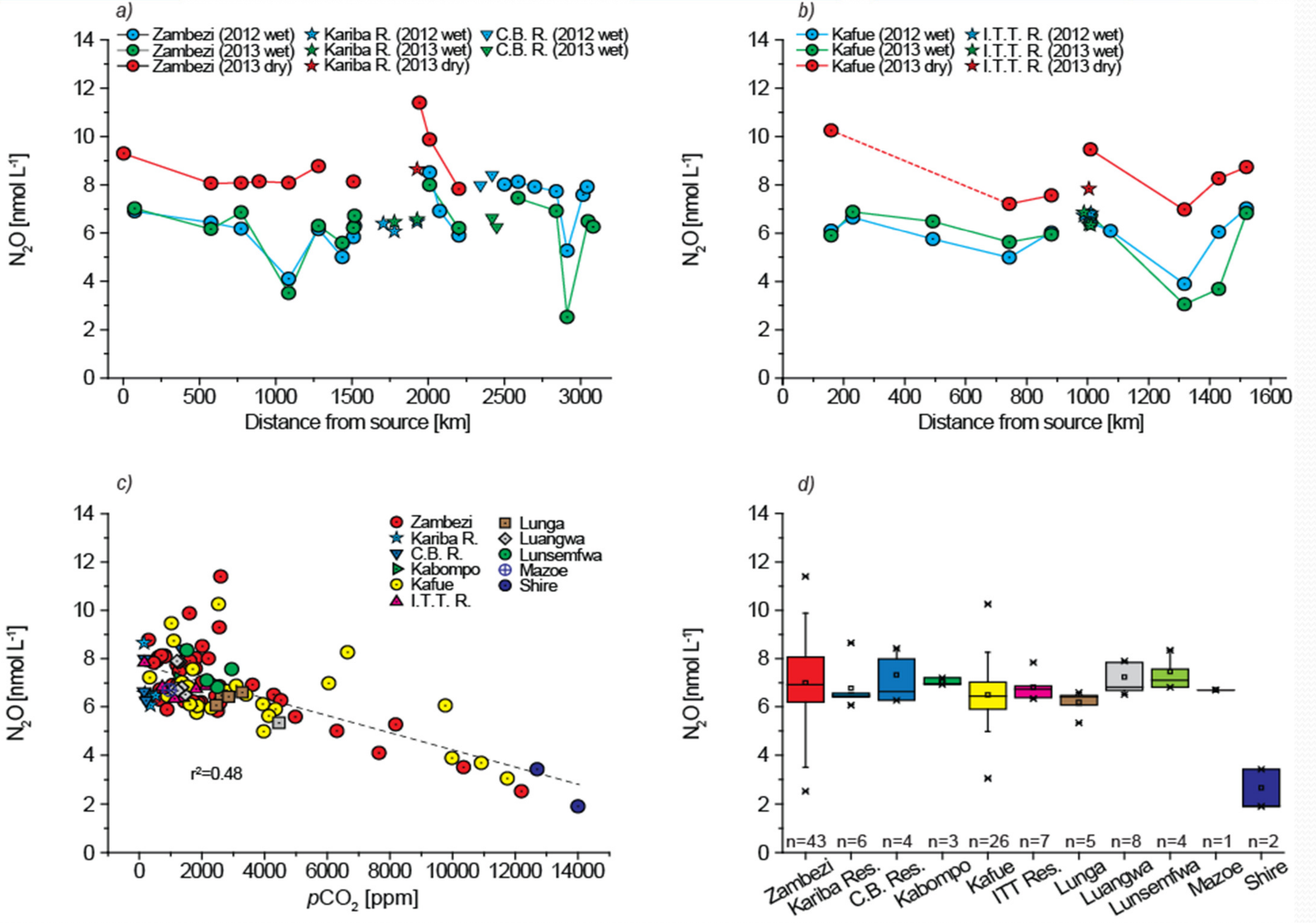
Temporal and spatial variability of pCO_2



Temporal and spatial variability of CH_4



Temporal and spatial variability of N_2O

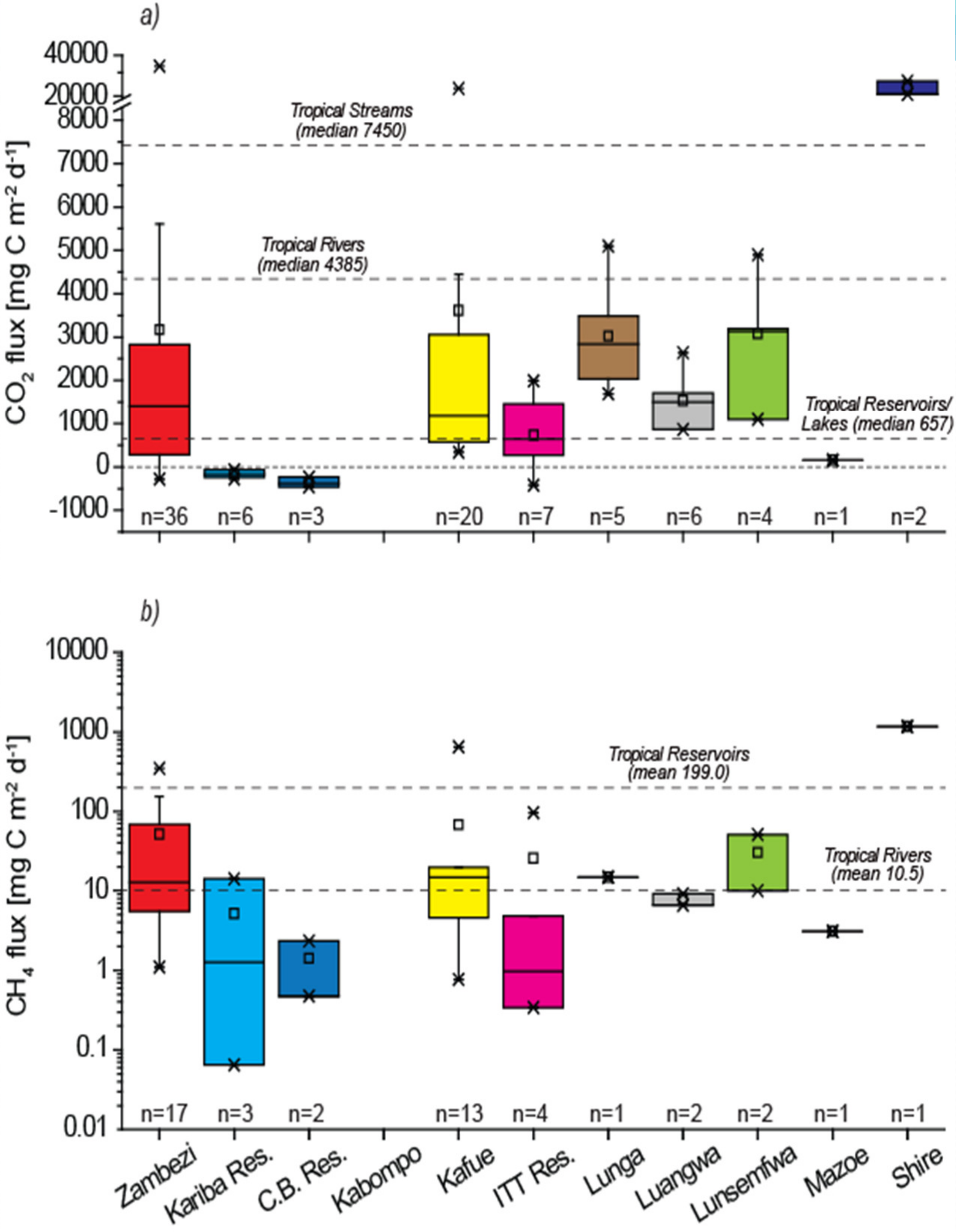


Patterns of GHG emissions

Dot lines in

a) suggest global median CO_2 emission levels for tropical rivers, streams and lakes/reservoirs based on Aufdenkampe et al., 2011

b) represent global mean CH_4 emission for tropical rivers and reservoirs based on Bastviken et al., 2011



Overall, there was no unidirectional pattern along the river stretch (i.e. decrease or increase towards the ocean), as the spatial heterogeneity of GHGs appeared to be determined mainly by the connectivity with floodplains and wetlands, and the presence of man-made structures (reservoirs) and natural barriers (waterfalls, rapids)

Highest CO_2 and CH_4 concentrations in the mainstream river were found downstream of extensive floodplains/wetlands. Undersaturated CO_2 conditions, in contrast, were characteristic for the surface waters of the two large reservoirs along the Zambezi mainstem (Kariba and Cahora Bassa).

Among tributaries, highest concentrations of both CO_2 and CH_4 were measured in the Shire River whereas low values were characteristic for more turbid systems such as the Luangwa and Mazoe rivers.

The inter-annual variability in the Zambezi River was relatively large for both CO2 and CH4, and significantly higher concentrations (up to two fold) were measured during wet seasons compared to the dry season

Overall, both concentrations and fluxes of CO_2 and CH_4 were well below the median/average values reported for tropical rivers, streams and reservoirs

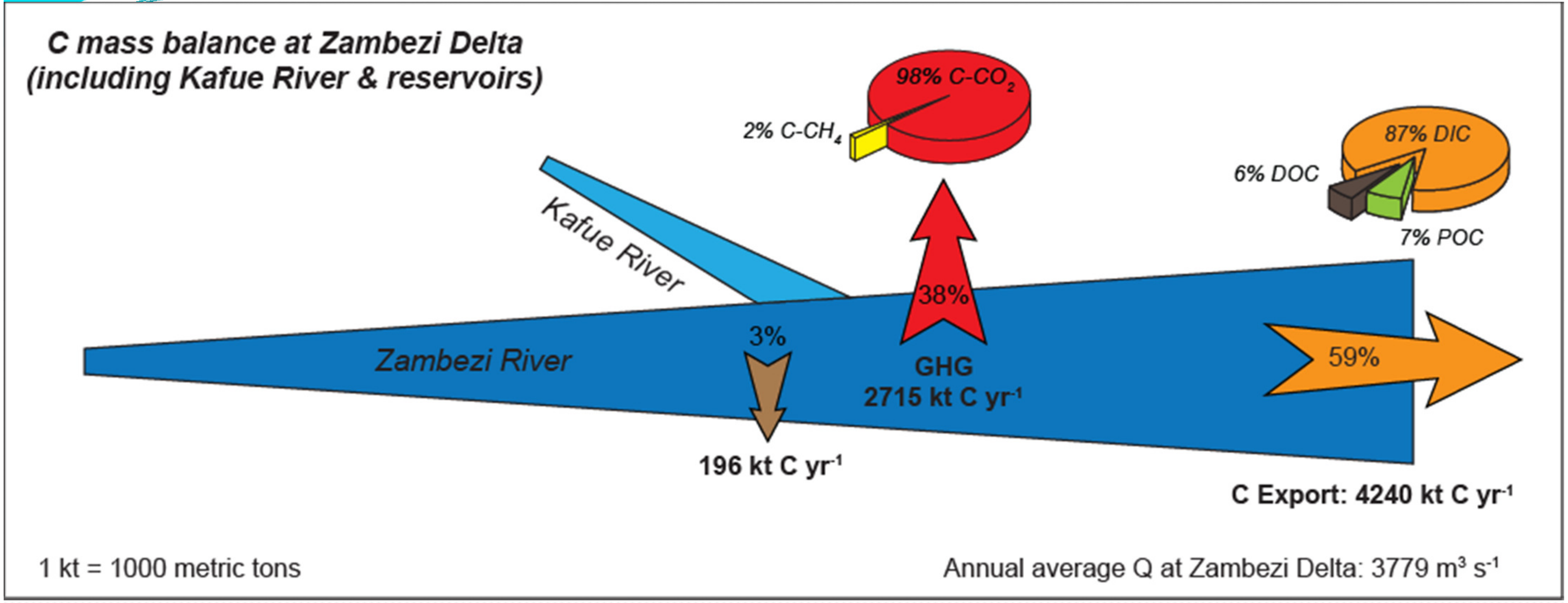
a)							
River/Reservoir	Area	CO_2 flux	CH_4 flux	CO_2	CH_4	Emission	Deposition
	$[\mathrm{km}^2]$	$[\mathrm{mg\ C\ m^{-2}\ d^{-1}}]$		$[\mathrm{kt\ C\ yr^{-1}}]$			
Kafue River without reservoirs	287	2962	20.0	310	2.1	312	-
Itezhi Tezhi Reservoir	364	737	25.8	98	3.4	101	16
Kafue Gorge Reservoir	13	737	25.8	3	0.1	4	1**
Kafue River with reservoirs	**664**	**1698***	**23.3***	**411**	**5.6**	**417**	**17**
Zambezi River without reservoirs	1879	4291	45.0	2943	30.8	2974	-
Kariba Reservoir	5364	-141	5.2	-276	10.1	-266	120
Cahora Bassa Reservoir	2670	-356	1.4	-347	1.4	-346	60**
Zambezi River with reservoirs	9913	641*	11.7*	2319	42.3	2362	180
Zambezi & Kafue Rivers with reservoirs	**10576**	**707***	**12.4***	**2731**	**48.0**	**2779**	**196**
b)							
River	Q	POC	DOC	DIC	POC	DOC	DIC
	$[\mathrm{m^3\ s^{-1}}]$	$[\mathrm{mg\ L^{-1}}]$			$[\mathrm{kt\ C\ yr^{-1}}]$		
Zambezi River at Delta	3779	2.6	2.2	30.8	306	263	3672
c)							
	Yield	Emission	Deposition	Export	Emission	Deposition	Export
	$[\mathrm{kt\ C\ yr^{-1}}]$				[%]		
Carbon Balance at Zambezi Delta	**7215**	**2779**	**196**	**4240**	**38**	**3**	**59**

a) Carbon emission estimates based on measured CO_2 and CH_4 fluxes (this work) and carbon removal by deposition in reservoirs based on available published data (Kunz et al., 2011a)

b) Carbon export loads to the ocean calculated using average literature river discharge at the Zambezi Delta and POC, DOC and DIC concentrations (this work) measured at the river mouth (ZBZ.19 and ZBZ.20) during 2012 and 2013 wet season campaigns

c) Carbon deposition in the Kafue Gorge and Cahora Bassa reservoirs (**) were estimated assuming same deposition rates of the Itezhi Tezhi and the Kariba reservoirs, respectively.

Carbon mass balance



Limitations to the mass balance:

a) Lack of direct discharge measurements at the river mouth (Delta)
b) Limiting the GHG measurement only to the Zambezi and Kafue rivers
c) Missing data on C removal by sedimentation in rivers

CO_2 and CH_4 uptake at Kariba and Cahora Bassa (76% of area) lowered the C emissions

Mass balance is consistent with previous figures of global C budgets (Cole et al., 2007; Battin et al., 2009)

4.0 Conclusions

- Overall, results of this catchment scale study demonstrate that riverine GHGs, despite their inter-annual and seasonal variations, appeared to be mainly controlled by the connectivity with floodplains/wetlands, the presence of rapids/waterfalls and the existence of large man-made structures along the aquatic continuum

- Although other values (^{13}C-DIC, DSi : Ca^{2+}) suggest the importance of both carbonate weathering as well as in-stream processes in controlling riverine DIC, the co-variation of pCO_2 with CH_4 suggest that dissolved gases in this river system originate largely from organic matter degradation

- When compared with other studied river systems in Africa, the range in GHG concentrations and fluxes in the Zambezi River Basin are below literature-based value for tropical rivers, streams and lakes/reservoirs

- The C mass balance for the entire river suggest that GHG emission to the atmosphere represent less than 40% of the total budget, with C export to the ocean (mostly as DIC) being the dominant component (59 %)

- The importance of GHG emissions in the overall budget is likely underestimated since our analyses did not take into account fluxes from the entire hydrological network (i.e. all tributaries), and since potentially large emissions that occur in the seasonally flooded wetlands and floodplains have not been estimated.

ADDITIONAL INFORMATION

Google: Biogeosciences/Zambezi River

http://ees.kuleuven.be/project/afrival/

www.biogeosciences-discuss.net/11/16391/2014/doi:10.5194/bgd-11-16391-2014

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END

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