# Dry Season Carbon Dynamics in Savannah Grassland and Rainforest Dominated River Basins of Madagascar.

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## Introduction

- Recent syntheses (see Cole *et. al.*, 2007; Battin *et. al.,* 2009; Aufdenkampe *et. al,* 2011) indicate that less than half the total of terrestrial-derived carbon (~1.9 Pg C $y^{-1}$) entering freshwater systems is ultimately exported to the oceans (~0.9 Pg C $y^{-1}$) in relatively equal quantities of inorganic and organic forms. Further, at least 0.8 Pg C $y^{-1}$ is evaded to the atmosphere as $CO_2$, whilst approximately 0.2 Pg C $y^{-1}$ becomes stored in aquatic sediments. Cole *et. al.* (2007) stress that these estimates remain conservative values. Constraining intermediate stages of carbon processing and transformation on local and regional scales will contribute to a more comprehensive understanding of the global carbon cycle, providing a foundation for predicting future conditions under changing climate and land-use scenarios.

- Relative to temperate basins, limited data exist on carbon processing and flux rates of tropical river basins (Battin *et. al.,* 2009), such as those in Africa. Madagascar, spatially small comparative to the mainland, contains a similar vegetation spectrum of C3 to C4 dominated basins, from east to west respectively. Previous research suggest up to 8-40 t hectare$^{-1}$ yr$^{-1}$ of soil is eroded from the landscape, the highest rates globally (Cox *et. al*., 2010). Much of this is contributed by mass failure features, termed *lavakas* ('hole') in local Malagasy, typical of the Hauts Plateaux in the central west of the country.

- The following presents select results of an initial campaign during the Malagasy dry season (July-September 2010).

## Site and Methods

- The Betsiboka basin (63,500 km$^2$) is the largest in Madagascar, experiencing a well defined wet-dry seasonality, with much of the catchment dominated by C4 dominated savannah grasslands (>80%, Still *et. al*., 2003). *Lavakas* are prevalent throughout the upper- and mid-basin, and contribute significant quantities of mineral and organic matter to the network.

- The Rianila basin (7,280 km$^2$), typical of the eastern Malagasy drainage networks, traverses a steep altitude gradient (from 1,450 m to 200 m over 46 km) through C3 dominated tropical forests. Annual precipitation is higher, although seasonal variability is lower, than within the Betsiboka basin.

- 43 and 16 sites were sampled in the Betsiboka and Rianila, respectively, for physico-chemical parameters, TSM, and POC, DOC, and DIC concentrations and $\delta^{13}C$ signatures, aquatic respiration and primary production rates, water-atmosphere $CO_2$ flux measurements, and soil and sediment carbon characteristics. Water bodies included streams, rivers, reservoirs and lakes.

- Other measured parameters include nutrient and major element concentrations, lignin and $^{14}C$-POC, -DOC and -DIC.

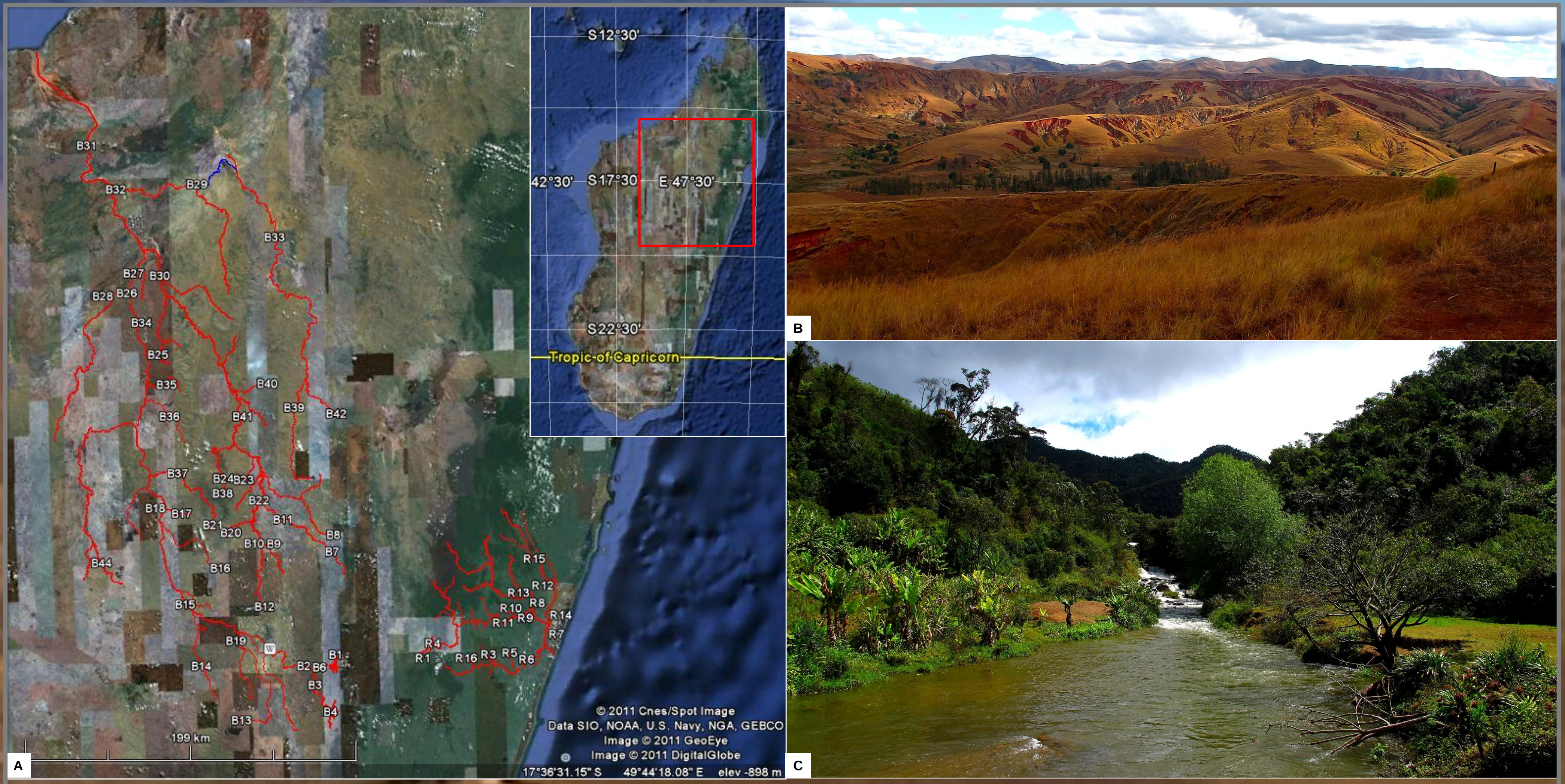


**Figure 1**: (A) Madagascar (inset) and digitisation of Betsiboka and Rianila basins. (B) C4 savannah grassland hillsides severely eroded by *lavakas* in the Betsiboka basin, Hauts Plateaux, central west Madagascar. (C) C3 tropical forest typical of the Rianila basin, eastern Madagascar.

## Results & Discussion

**Table 1**: Comparison of average total suspended matter (TSM), carbon specie concentrations and $\delta^{13}C$ signatures for the Betsiboka, Rianila and African data compilation (inc. the Congo, Tana, Gambia, Niger and rivers of Lake Kivu).

| | Betsiboka (n = 39) | Rianila (n = 16) | Africa | |
|---|---|---|---|---|
| | Average (± S.D.) | Average (± S.D.) | Average (± S.D.) | n |
| TSM (mg/L) | 36.1 (± 40.1) | 14.5 (± 9.0) | 184.8 (± 822.5) | 536 |
| POC (mg/L) | 0.78 (± 0.49) | 0.92 (± 0.48) | 5.58 (± 15.97) | 449 |
| POC/PN | 13.8 (± 5.2) | 13.0 (± 1.8) | 11.3 (± 3.5) | 257 |
| %POC | 5.4 (± 5.4) | 8.1 (± 4.1) | 8.6 (± 8.6) | 399 |
| $\delta^{13}C_{POC}$ | -22.8 (± 2.2) | -26.5 (± 0.9) | -25.4 (± 2.7) | 270 |
| DOC (mg/L) | 1.07 (± 0.61) | 1.56 (± 0.67) | 8.94 (± 8.71) | 652 |
| $\delta^{13}C_{DOC}$ | -24.8 (± 1.8) | -27.8 (± 0.6) | -25.7 (± 2.5) | 245 |
| DOC/POC | 1.8 (± 1.2) | 2.0 (± 1.0) | 3.8 (± 7.5) | 338 |
| $\delta^{13}C_{DIC}$ | -6.0 (± 1.8) | -10.6 (± 2.5) | -12.9 (± 5.6) | 492 |

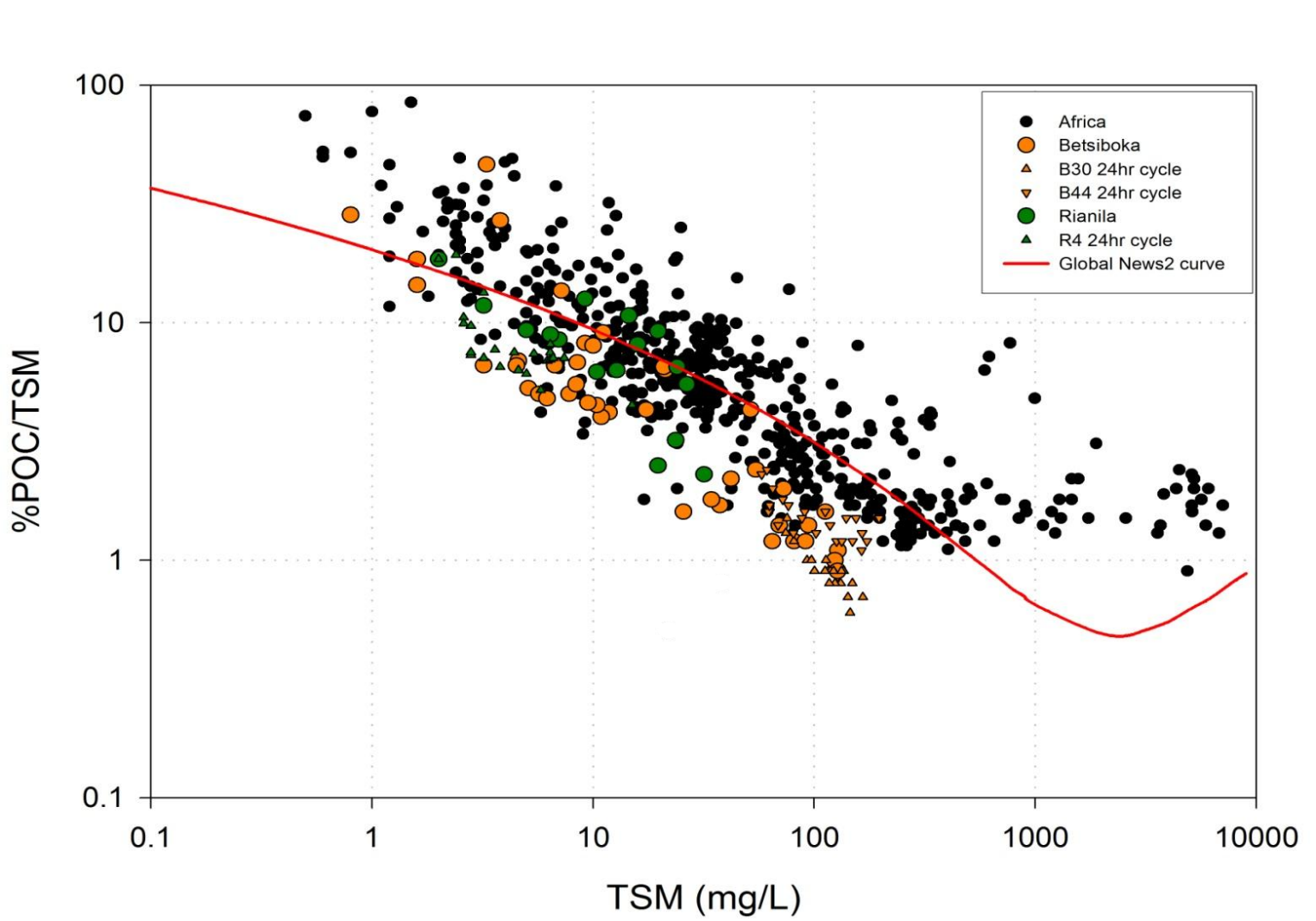


**Figure 2**: Relation between %POC and total suspended matter (TSM) concentration and % particulate organic carbon (POC) for the Betsiboka, Rianila and African data compilation. Output from the Global News2 model is also shown in red.

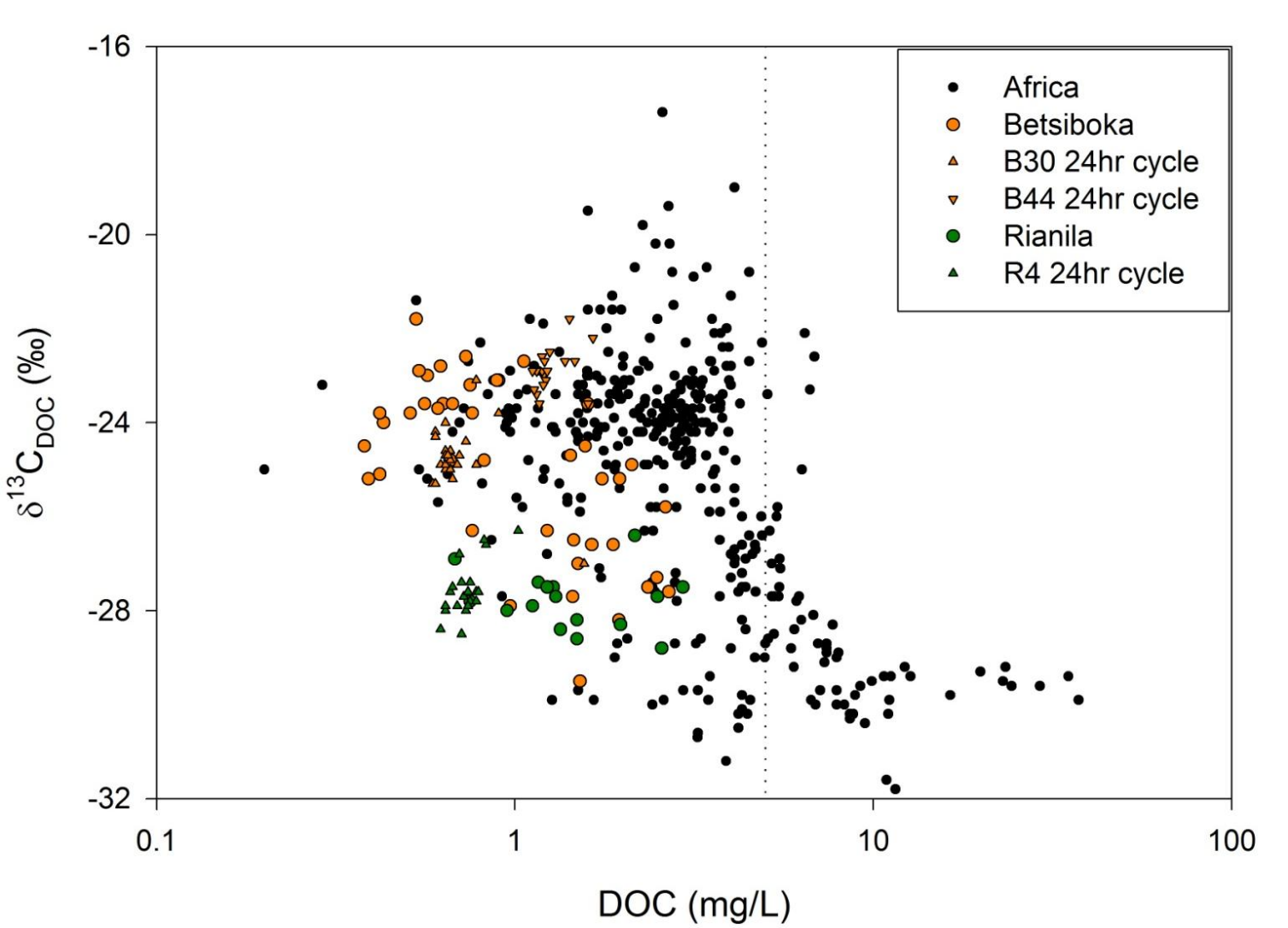


**Figure 3**: Relation between dissolved organic carbon (DOC) concentration and $\delta^{13}C_{DOC}$ for the Betsiboka, Rianila and African data compilation. The vertical dashed line (5 mg/L) is the global average DOC concentration reported by Meybeck (2005).

- Concentrations of TSM, POC and DOC were considerably lower in both the Betsiboka and Rianila than values observed in other African basins (**Tab. 1**), although Malagasy data only represent dry season whilst African data is more reflective of annual conditions.

- Although the Betsiboka is spatially dominated by C4 savannah grasslands (measured $\delta^{13}C$ value: -13.3 ± 0.9 ‰), this is not apparent in $\delta^{13}C_{POC}$ or $\delta^{13}C_{DOC}$ signatures, which display a mixed C3 and C4 terrestrial OC input. Rianila POC and DOC more closely reflect basin vegetation $\delta^{13}C$ signatures (-29.9 ± 0.1‰).

- %POC was consistently lower at most TSM concentrations (**Fig. 2**) than predicted by the Global News2 (based on Ludwig *et. al*., 1996) model outputs in both the Betsiboka and Rianila, and situated on the lower end of the range for African basins.

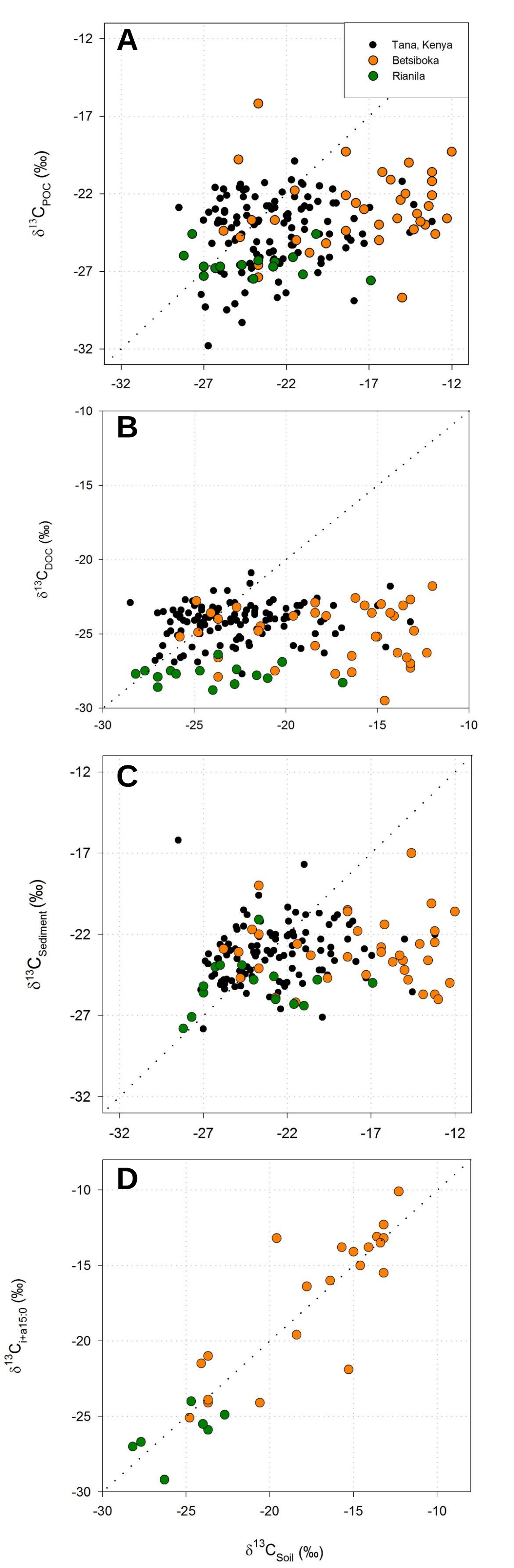
- The low %POC trend is likely a factor of the typical erosion processes of much of the Malagasy soil profiles. The characteristic formation of *lavakas* results in direct addition to fluvial waters of organically depleted, deep soil particulate matter in large quantities relative to the overlying, more fresh, organically enriched soil components.

- DOC concentrations (**Fig. 3**) for the Betsiboka and Rianila were low compared to other African basins and the global average of 5 mg/L reported by Meybeck (2006).

- DOC concentrations were generally lower in the C4 dominated Betsiboka basin than the C3 dominated Rianila basin, as observed in other comparisons of C3/C4 basins, even though the average Betsiboka $\delta^{13}C_{DOC}$ (-24.8 ± 1.8 ‰) indicates a strong influence of terrestrial C3 organic matter input.

- Our low DOC concentrations agree with the unusually low concentrations (~0.5 mg/L) measured in the freshwater end of the Betsiboka estuary by Ralison *et. al.* (2008).

**Figure 4**: Soil $\delta^{13}C_{OC}$ for the Betsiboka, Rianila, and the Tana, Kenya (unpublished data) and (A) $\delta^{13}C_{POC}$, (B) $\delta^{13}C_{DOC}$, (C) sediment $\delta^{13}C_{OC}$, and (D) phospho-lipid fatty acid $\delta^{13}C_{i+a15:0}$ bacterial marker. Dotted diagonal line in each figure represents a 1:1 relationship.



- Soil $\delta^{13}C_{OC}$ is considered reflective of the proportion of C3:C4 vegetation within a drainage basin. Although, particularly in the C4 dominated Betsiboka, results show $\delta^{13}C_{POC}$, $\delta^{13}C_{DOC}$ and sediment $\delta^{13}C_{OC}$ (**Fig. 4A-C**) were consistently more depleted in $^{13}C$ than would be expected from the surrounding vegetation.

- Preferential uptake of $^{13}C$-enriched (C4) organic matter by soil microbes may result in more $^{13}C$-depleted aquatic POC and DOC pools. General agreement between soil $\delta^{13}C_{OC}$ and soil microbe phospho-lipid fatty acid $\delta^{13}C_{i+a15:0}$ (**Fig. 4D**) indicate this is not the case for the Betsiboka or Rianila, although further analysis of sediment and in-stream microbial biomarkers may offer further insight.

- The lower than expected contribution of C4 organic matter to the POC and DOC pools is often observed in C4 savannah grassland dominated drainage basins (see Bird *et. al.,* 1994), especially under dry season conditions. The majority of dissolved and particulate OC input is sourced from the C3 dominated riparian fringe, as is commonly present in the Betsiboka, with the wider C4 dominated grassland largely disconnected from fluvial waters due to decreased surface runoff and throughflow resulting from seasonal aridity.

- Although quite variable throughout, $CO_2$ flux measurements were generally higher in the Rianila (120.2 ± 82.5 mmol $CO_2$ $m^{-2}$ $d^{-1}$) than the Betsiboka (70.4 ± 87.9 mmol $CO_2$ $m^{-2}$ $d^{-1}$).

- Despite the difference between the Betsiboka and Rianila for calculated annual $CO_2$ flux (**Tab. 2**), there was little difference in measured aquatic respiration rates.

- Net $CO_2$ uptake from the atmosphere to the river was measured at multiple sites in the lower reaches of the Betsiboka, though never in the Rianila basin.

- Median annual $CO_2$ evasion for both basins was much lower than values reported by Aufdenkampe *et. al*. (2011).

**Table 2**: Annual $CO_2$ flux range, average, and median values for the Betsiboka and Rianila. The median value for rivers and streams, respectively, of the tropics (see Aufdenkampe *et. al.*, 2011) is also presented for comparison. Average aquatic respiration rate (R) is also shown for the study basins.

| | Betsiboka | Rianila | Tropics |
|---|---|---|---|
| Min. $CO_2$ flux (g C $m^{-2}$ $y^{-1}$) | -264.9 | 100.4 | |
| Max. $CO_2$ flux (g C $m^{-2}$ $y^{-1}$) | 1550.9 | 3045.2 | |
| Median $CO_2$ flux (g C $m^{-2}$ $y^{-1}$) | 100.8 | 479.5 | 1600-2720 |
| Average $CO_2$ flux (g C $m^{-2}$ $y^{-1}$) | 185 ± 294 | 848 ± 927 | |
| Ave. R (µmol $L^{-1}$ $h^{-1}$) | 0.653 ± 0.29 | 0.693 ± 0.37 | |

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## Conclusions

- TSM, POC and DOC concentrations were all below African averages, although large increases will be expected in the wet season campaign (Nov-Dec 2011).

- The C3 riparian fringe is the dominant organic carbon source during the dry season, particularly in the Betsiboka, despite the extensive C4 vegetation cover.