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# Riverine dissolved organic carbon in Rukarara River Watershed, Rwanda

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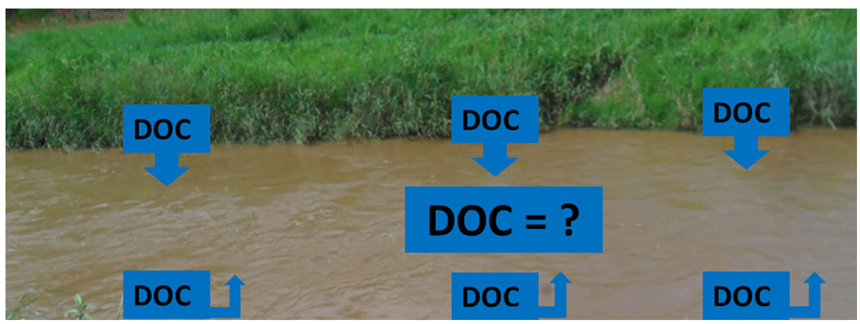
## HIGHLIGHTS

- Eight percent of daily net carbon produced in the watershed is lost through rivers.
- Stream in natural forest had more dissolved organic carbon (DOC) than those in croplands.
- Flow volume and stream DOC had a positive relationship in the watershed.
- Stream DOC concentration and lag time is linked to topography, land use and cover

## GRAPHICAL ABSTRACT

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## ABSTRACT

Dissolved organic carbon (DOC) loading is rarely estimated in tropical watersheds. This study quantifies DOC loading in the Rukarara River Watershed (RRW), a Rwandan tropical forest and agricultural watershed, and evaluates its relationship with hydrological factors, land use and land cover (LULC), and topography to better understand the impact of stream DOC export on watershed carbon budgets. The annual average load for the study period was 977.80 kg C, which represents approximately 8.44% of the net primary productivity of the watershed. The mean daily exports were 0.37, 0.14, 0.075 and 0.32 kg C/m$^2$ in streams located in natural forest, tea plantation, small farming areas, and at the outlet of the river, respectively. LULC is a factor that influences DOC loading. The quick flow was the main source of stream DOC at all study sites. Stream DOC increases with increasing water flow, indicating a positive relationship. Thus, the expectation is that a change in land cover and/or rainfall will result in a change of stream DOC dynamics within the watershed. Topography was also found to influence the dynamics of stream DOC through its effect on overland flow in terms of drainage area and total length of flow paths. Tea plantations were located in areas of high drainage density and projected increase of rainfall in the region, as a consequence of climate change, could increase stream DOC content and affect stream water quality, biodiversity, balance between autotrophy and heterotrophy, and bioavailability of toxic compounds within the RRW.


## 1. Introduction

The role of inland waters in the global carbon cycle is now widely recognized at the catchment, regional and global scales (Cole et al., 2007; Battin et al., 2009). Streams receive carbon from in-stream and terrestrial production that is processed or exported downstream (Mattsson et al., 2009; Williams et al., 2010; Alvarez-Cobelas et al.,

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2012). Another source of carbon in rivers is sediment and rock weathering processes in carbonates and gypsum-rich deposits (Salimon et al., 2013). Carbon enters streams mainly through surface runoff and by groundwater as particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved inorganic carbon (DIC) (Johnson et al., 2006; Aufdenkampe et al., 2011).

This study focuses on DOC since it is the major organic pool in most aquatic ecosystems (Wetzel, 2001). Stream-water DOC is of particular interest because it serves as an important resource for downstream ecosystems (Amon and Meon, 2004; Post et al., 2009; Pagano et al., 2014) and is beneficial for aquatic biota (Sucker and Krause, 2010). Organic carbon in streams serves as an important modulator because it modifies the influences and consequences of other chemicals and processes (Prairie, 2008). However, changes in DOC levels in water are also of environmental concern: high DOC concentration can affect surface water quality, water metabolism, balance between autotrophy and heterotrophy, nutrient uptake and bioavailability of toxic compounds, and the growth of microorganisms (Munson and Gherini, 1993; Delpla et al., 2009; Fernández-Pérez et al., 2005; Erlandsson et al., 2011; Stanley et al., 2012).

DOC concentration in natural waters has changed over the past few decades; for example, in some areas in North America and northern Europe, it may have doubled (Evans et al., 2005; Monteith et al., 2014; SanClements et al., 2012; Pagano et al., 2014). In a few other areas, a decrease or no increase of DOC in waters was reported (Pagano et al., 2014). Regarding the increase of DOC in natural waters, its drivers in some areas are up for debate. Possible factors include changes in air temperature (Freeman et al., 2001), increased precipitation (Worrall and Burt, 2008; Sucker and Krause, 2010), land use changes (Findlay et al., 2001; Sucker and Krause, 2010), increased atmospheric carbon dioxide (Harrison et al., 2008; Sucker and Krause, 2010; Kane et al., 2014) and decreased atmospheric sulfur deposition (Fowler et al., 2005; Sucker and Krause, 2010; Rowe et al., 2014) and atmospheric nitrogen deposition (Singh et al., 2016). Pagano et al. (2014) mention the combined effect of increased atmospheric $CO_2$ concentration and temperature. This increased atmospheric $CO_2$ stimulates plant primary production (Freeman et al., 2004) whereas global warming may influence DOC export by altering decomposition and mineralization of organic matter (Worrall et al., 2003), water budget and discharge, which then increases DOC concentrations (Hongve et al., 2004). Consequently, an increase of DOC in freshwaters may be linked with climate change, it is therefore important to monitor temporal variations of DOC concentration in natural waters to anticipate climate impacts on carbon dynamics and water resources.

Most studies of DOC changes in waters have been performed in temperate ecosystems in North America and Europe. Thus, there is a need to monitor DOC changes in waters in other geographical areas, such as tropical regions, where precipitation and temperature are projected to continue to increase (Paeth et al., 2009). For example, in Rwanda, temperatures have increased 1.4 °C from 1970 to 2008, and this increase is projected to reach 1.5 °C to 3 °C by the 2050s (Hove et al., 2010). Average annual rainfall increased about 10% during the same time interval (Warnest et al., 2012). It follows that changes in climate will alter water budgets in tropical watersheds, with implications for DOC in natural waters. It is important to monitor how hydrological variability can affect DOC in natural waters in tropical watersheds in order to better understand this issue and its implications for the global carbon budget.

Studies suggest that tropical rivers exhibit the highest riverine DOC flux to oceans (Gu et al., 2009; Bouillon et al., 2014), but their inclusion in carbon budgets stems from datasets that are missing well-defined values in the tropics since most studies of riverine DOC have been performed in temperate and arctic rivers (Stedmon et al., 2011; Spencer et al., 2012; Lambert et al., 2015). Recent research (e.g. Palviainen et al., 2016; Ren et al., 2016; Singh et al., 2016) has shown that land cover is a useful predictor of riverine DOC in temperate biomes, but the situation may be different in tropical regions.

The objective of this study is to determine the relationship between stream water DOC loading, hydrological factors, topography and land cover in a tropical watershed for a better understanding of the impact of stream DOC export on watershed carbon budget. This study specifically characterizes the spatial and temporal variation of stream DOC and describes the relationship between stream DOC, water level, water discharge and land cover. It estimates the DOC loading in the Rukarara River and some of its tributaries, and the loss of DOC through fluvial export compared to the net primary productivity of the watershed. We hypothesize that the variability in hydrology and land cover will alter runoff, discharge characteristics and carbon dynamics in tropical watersheds, and this will be expressed in variable export of soil DOC into streams.

## 2. Material and methods

### 2.1. Study area

The study was carried out in the Rukarara River Watershed (RRW), a catchment that drains an area of 493.5 km$^2$ (Fig. 1a) in southwestern Rwanda. The catchment landscape is composed of mountainous terrain with elevations from 1541 to 2924 m., and slopes from 0° to 68°. Annual precipitation ranges from 1300 to 1450 mm, and the temperature from 15 °C to 25 °C. The soils are acid ($3.6 < pH < 5.0$) and mainly of the Ultisol, Entisol, and Inceptisol types. Across the watershed, 13 main streams drain waters into Rukarara River.

The watershed is a part of the Nyungwe Natural Forest, and also includes cultivated forests and croplands with annual or perennial crops. Annual crops include, for example, common beans, maize, and banana plantations; the perennials are primarily tea and cassava. All crops, except tea, are food crops used by small farmers who use simple handheld tools like hoes to prepare their cropland. The farmers rotate groups of crops, for example, common bean and sorghum, and also mix in others like maize. Industrial fertilizers are normally used for tea plantations. Most farmers use organic manure for other crops. As is the case for most Rwandans, the primary source of energy for inhabitants in Rukarara River Watershed is mostly biomass in form of wood, branches, leaves and crop residues.

### 2.2. Data collection and analysis

#### 2.2.1. Water stage data

To collect data of stream stage, gauging stations were installed at the four sites (Fig. 2). At each site, an automatic pressure transducer was installed for recording the water level, as a function of pressure, every 15 min. The transducers were protected by iron stilling wells, fixed with concrete and closed with padlocks. Water stage data were collected from March 2015 to February 2017 at four sites namely natural forest, tea, farm and outlet (Fig. 2). Water stage data were used together with flow data to produce rating curves. The rating curves were used to predict non-measured flow data that have been used in estimation of annual DOC load.

#### 2.2.2. Water velocity and flow data

On several occasions, data of velocity were measured using small and middle size current meters by the Six-Tenths-Depth method (Dingman, 1984). A medium size current meter (current meter number: C31 261020 and propeller number: 2-252132) was used for velocity measurement at the outlet, and the tea and natural forest streams. A current meter appropriate for the smallest flows (current meter number: C2 253194 and propeller number: 272477) used for measuring velocity data for the farm stream. The stream flow was measured along a number of vertical segments lying along the cross sectional width of the channel. The number of verticals depended on the width of the stream and was determined in the sense that the flow in each subsection should be <5% of the total and the difference in velocity values