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Organic carbon concentrations and transport in small mountain rivers, Panama

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A B S T R A C T

Tropical small mountainous rivers (SMRs) are increasingly recognized for their role in the global export of dissolved organic carbon (DOC) to the oceans. Here we utilize the Isthmus of Panama as an ideal place to provide first-order estimates of DOC yields across a wide assemblage of bedrock lithologies and land cover practices. Samples for dissolved organic carbon (DOC) analysis were collected across Panama along an E–W transect from the central Panama area to the Costa Rican border for 24 mainstem rivers, 3 large tributary rivers, and one headwater stream. Sampling occurred during both the wet and the dry seasons. DOC concentrations during the wet season are higher than during the dry season in all but three of the rivers. Concentrations vary greatly from river to river and from season to season, with values as low as 0.64 mg l^{-1} to greater than >25 mg l^{-1} with the highest concentrations observed for the rivers draining Tertiary marine sedimentary rocks in the Burica and Azuero peninsulas. DOC yields from Panamanian rivers (2.29–7.97 tons/km^2/y) are similar to or slightly lower than those determined for other tropical SMR systems. Areas underlain by Tertiary aged sediments exhibited significantly higher mean DOC yields compared to their igneous counterparts, despite maintaining substantially lower aboveground carbon densities, suggesting the important influence of lithology. Finally, regression analyses between DOC yields and select watershed parameters revealed a negative and statistically significant relationship with maximum and mean gradient suggesting lower soil retention times may be linked to lower DOC yields.

1. Introduction

The transport of organic carbon from the terrestrial landscape to the ocean is a major process in the global carbon cycle (Ludwig et al., 1996; Aitkenhead and McDowell, 2000; Raymond and Bauer, 2001; Lyons et al., 2002; Cole et al., 2007). The amount of organic matter transported and buried in marine sediments and terrestrial deposits, compared to the amount of carbon that is recycled in both the terrestrial landscape and the aquatic system, has real importance with regard to global carbon sequestration (Cole et al., 2007). Recently, tropical and subtropical mountainous regions of the world have been shown to play an important role in the transport of particulate organic carbon (POC) and dissolved organic carbon (DOC) to the global ocean (Kao and Liu, 1997; Blair et al., 2003; Gomez et al., 2003; Komada et al., 2004; Carey et al., 2005; Hilton et al., 2012; Lloret et al., 2011, 2013). However, there is still a need to substantiate these suggestions as datasets acquired to date are generally from isolated localities that are of limited spatial extent. This lack of organic carbon flux data is particularly true for the humid tropics which contain as much as 30% of the world's total soil organic carbon (Batjes, 1996). In addition, these studies often overlook how factors such as lithology, stream geomorphology and ecosystem modification can ultimately modify these rates of DOC export.

This paucity of data has also complicated the search for controls on organic matter export from SMR locales. In fact in many regions

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of the world fluxes and yields have been determined by extrapolation and by modeling (Ludwig et al., 1996; Lloret et al., 2013). Steep slopes and high rainfall have been attributed to elevated POC yields (Hilton et al., 2012), much of which is transported to the ocean during periodic to aperiodic intense precipitation events (Goldsmith et al., 2008; Hilton et al., 2008; Wohl et al., 2012). However, these same factors have been shown to have a varying relationship with DOC yields (Guyot and Wasson, 1994; Townsend-Small et al., 2005; Lloret et al., 2013) as thin soils prevent the building up of organic material in shallow soils. To discern elevation effects on DOC concentrations in SMRs is often further complicated by the influence of anthropogenic activities associated with higher population densities at lower altitudes (Yang et al., 2013). Furthermore, studies on DOC export from subtropical and tropical SMRs tend to focus on monolithic settings consisting of either uplifted sedimentary/lightly metamorphosed terrains (Kao and Liu, 1997; Carey et al., 2005; Alin et al., 2008) or volcanic islands (Lloret et al., 2011, 2013) with limited inter-basin climate variability. Thus, an understanding of the role of these constraining factors is crucial before extrapolating values to other settings for modeling purposes.

This paper addresses existing knowledge gaps by presenting both wet and dry seasons DOC concentrations for 24 mainstem rivers, 3 tributary rivers, and a headwater stream from central and western Panama. In addition, DOC yields have been calculated from watersheds where river discharge measurements exist. DOC yields are subsequently compared to a series of hydrologic, lithologic, geomorphologic, and land cover parameters in a search for controls. These data substantially improve our overall knowledge of carbon yields from tropical watersheds.

2. The west-central Panama study area

Panama is located in the humid seasonal tropics and has a tropical climate that is characterized by constant high temperature at sea level and low elevation, distinct wet and dry seasons, and annual rainfall exceeding evapotranspiration across most of the country (Kottek et al., 2006; Peel et al., 2007). Temperatures are uniformly high across the country, with each month of the year having an average temperature of 18 °C or higher and seldom exceeding 32 °C, except in the higher parts of the mountain ranges where frosts can occur during winter months.

Rainfall across Panama is strongly seasonal, with pronounced wet and dry seasons, and varies regionally from less than 1.3 m to nearly 7 m per year (Rand and Rand, 1982; Cavelier et al., 1996). Because the primary source of moisture to Panama's precipitation comes from the Atlantic Ocean, the Atlantic coastal region receives greater rainfall than the Pacific coastal region on the leeward side of the continental divide. Rain falls throughout the year along the Caribbean coast, so that annual accumulations on the north slopes of the Cordillera Central can range 3000–7000 mm, whereas the Pacific coast of central Panama and the Azuero peninsula have a tropical dry and wet climate with annual rainfall of <2000 mm. The Cordillera Central creates an elevation barrier and, therefore, a strong climate gradient from north to south across Panama that generates higher precipitation and consequent greater runoff, erosion, and river incision on the Caribbean side of Panama compared to the Pacific side. About 90% of the annual precipitation falls during the rainy season between May and December. This wet period is followed by a marked dry season from January to April. River discharge correlates well with precipitation. Since wet season storms approach Panama from the north, the Caribbean slope of the Cordillera Central is moist and heavily forested by comparison to the Atlantic side, which has a longer dry season, receives less precipitation, and therefore is comparatively drier and much more developed (Condit et al., 2001). The H- and O-isotopic composition of surface waters in Panama becomes more depleted with distance from the Caribbean coast, documenting progressive rainout as the moisture-rich air masses move southward across the country (Lachniet and Patterson, 2006; Harmon et al., 2009).

The land that today composes Panama formed over the past 140 million years as a consequence of Caribbean, South American, Cocos, and Nazca plate interactions as an island arc archipelago developed on Mezozoic oceanic crust of the Caribbean plate and interacted with associated marine sedimentary basins (Molnar and Sykes, 1969). Geologically, Panama consists of a mosaic of bedrock lithologies that range from hydrothermally altered marine oceanic crust, intrusive mafic to intermediate composition, igneous rocks, a broad array of volcanic rock compositions, and uplifted loosely consolidated marine and clastic sedimentary rocks deposited unconformably upon the igneous rocks of the volcanic arcs during Tertiary time in the Bocas del Toro region, the Burica and Azuero peninsulas, and in portions of the Trans-Isthmus, Colon, and East Panama regions (Coates et al., 2004; Wegner et al., 2011). Silicate rocks across Panama comprise a broad range of volcanic and intrusive lithologies. Tholeiitic to low-*K* calc-alkaline basalts and andesites dominate the extrusive suite, whereas gabbros to granodioirites are the most common intrusive rocks. As a consequence, the solute signature of Panamanian rivers, which is largely acquired in watershed headwater areas (Harmon et al., 2013), is broadly similar in terms of major elements, except where rivers are developed predominantly on rhyolite and granite or on associated Tertiary shallow marine sediments. The Panama land bridge, which presently forms the terrestrial connection between North and South America, formed during the past few million years by tectonic amalgamation and transpressive faulting of these igneous rocks at this active plate margin (Coates and Obando, 1996).

Across the tropics, oxide and clay minerals accumulate as a thick mantle of residual soil develops above active bedrock weathering in the critical zone. The geomorphic situation in Panama is characteristic of the mountainous tropics, where (i) thick, cation-depleted soils are present on ridges and topographic high ground, (ii) soils on mountain slopes are thin and cation depleted, and (iii) lowland soils are highly variable in both thickness and composition. The dominant soil type in much of Panama can be described as broadly saprolitic, although some minor surficial soil deposits derived from marine sediments are important locally. Like saprolitic soils across the humid tropics, these soils generally consist of clay- and silt-size particles that have been depleted of most alkali and alkaline earth cations, leaving a matrix consisting primarily of oxides of iron and aluminum (e.g. Stallard, 1985). Where quartz-bearing lithologies are present, soils will tend toward a sandy texture having a high permeability, whereas soils on mafic and intermediate volcanic terrains where quartz is absent tend to be fine-grained and are characterized by a decreased porosity and low hydraulic conductivity. It is not uncommon to find multiple soil types in close geographic proximity.

Because of its diverse tropical climate, Panama has one of the world's most varied ecosystems and is noted for its species richness (Myers et al., 2000). Forests dominate across mountain and upland areas, with secondary scrub forest, grasslands, and crops present to varying extents across the lowlands areas and coastal plains. Although nearly 40% of Panama is still wooded, deforestation is a continuing threat to the rain-drenched woodlands. Tree cover has been reduced by more than half over the past fifty years and there is concern that this deforestation is causing soil erosion and affecting the river chemical quality. Subsistence farming is practiced widely across the country and secondary forests arise when low-productivity agricultural land and pastures are abandoned.