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Climatic and geomorphic drivers of plant organic matter transport in the Arun River, E Nepal

Bernd Hoffmann[a,*], Sarah J. Feakins[b], Bodo Bookhagen[a], Stephanie M. Olen[a], Danda P. Adhikari[c], Janardan Mainali[d], Dirk Sachse[a,e]

[a] Universität Potsdam, Institut für Erd- und Umweltwissenschaften, Karl-Liebknecht-Strasse 24–25, 14476 Potsdam-Golm, Germany
[b] University of Southern California, Department of Earth Sciences, Los Angeles, CA 90089, USA
[c] Tribhuvan University, Department of Geology, Kathmandu, Nepal
[d] University of North Carolina Wilmington, Department of Geography & Geology, Wilmington, USA
[e] GFZ German Research Centre for Geosciences, Section 5.1, Geomorphology, Potsdam, Germany

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ABSTRACT

Fixation of atmospheric CO_2 in terrestrial vegetation, and subsequent export and deposition of terrestrial plant organic matter in marine sediments is an important component of the global carbon cycle, yet it is difficult to quantify. This is partly due to the lack of understanding of relevant processes and mechanisms responsible for organic-matter transport throughout a landscape. Here we present a new approach to identify terrestrial plant organic matter source areas, quantify contributions and ascertain the role of ecologic, climatic, and geomorphic controls on plant wax export in the Arun River catchment spanning the world's largest elevation gradient from 205 to 8848 m asl, in eastern Nepal. Our approach takes advantage of the distinct stable hydrogen isotopic composition (expressed as δD values) of plant wax *n*-alkanes produced along this gradient, transported in river waters and deposited in flood deposits alongside the Arun River and its tributaries. In mainstem-flood deposits, we found that plant wax *n*-alkanes were mostly derived from the lower elevations constituting only a small fraction (15%) of the catchment. Informed by remote sensing data, we tested four differently weighted isotopic mixing models that quantify sourcing of tributary plant-derived organic matter along the Arun and compare it to our field observations. The weighting parameters included catchment area, net primary productivity (NPP) and annual rainfall amount as well as catchment relief as erosion proxy. When weighted by catchment area the isotopic mixing model could not explain field observations on plant wax δD values along the Arun, which is not surprising because the large arid Tibetan Plateau is not expected to be a major source. Weighting areal contributions by annual rainfall and NPP captured field observations within model prediction errors suggesting that plant productivity may influence source strength. However weighting by a combination of rainfall and catchment relief also captured the observed δD value pattern suggesting dominantly erosive control. We conclude that tributaries at the southern Himalayan front with high rainfall, high productivity, high relief and high erosion rates dominate plant wax exports from the catchment.

1. Introduction

Fixation of atmospheric carbon in terrestrial organic matter and subsequent export into marine basins is one of the key mechanisms responsible for long term carbon burial with a direct impact on global atmospheric CO_2 levels (Berner, 1990; Burdige, 2005). In the Neogene Ganges–Brahmaputra river system, the transfer and burial of organic matter (OM), has been suggested to be more important for atmospheric CO_2 drawdown than the weathering of silicate rocks (France-Lanord and Derry, 1997). Whereas total OM fluxes to marine sinks have previously been estimated using a variety of different methods (France-Lanord and Derry, 1997; Galy et al., 2015, 2011; Goñi et al., 1997; Hedges et al., 1994, 1986; Schlünz and Schneider, 2000; Weijers et al., 2009), other studies have sought to understand the sourcing of OM within large river catchments (Bouchez et al., 2014; Galy et al., 2011; Goñi et al., 2014, 2000; Hedges et al., 2000; Kim et al., 2012; Ponton et al., 2014; Tao et al., 2015). Erosion and geomorphic

* Corresponding author.
E-mail address: hoffmann@geo.uni-potsdam.de (B. Hoffmann).

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characteristics have been suggested to control catchment scale OM transport (Clark et al., 2013; Galy et al., 2015). But also the significance of runoff for non-petrogenic OM mobilization, in particular triggered by rainstorm events, is increasingly acknowledged (Clark et al., 2013; Hilton et al., 2012; Smith et al., 2013; West et al., 2011). However, climatic and geomorphic drivers are both relevant for organic carbon erosion and mobilization as indicated by several prior studies (Clark et al., 2013; Hilton et al., 2012; Kao and Liu, 1996; Smith et al., 2013; Townsend-Small et al., 2008; Wheatcroft et al., 2010). Specific biomarkers for plants and in particular compound specific isotopic analyses offer promise for tracing plant components of terrestrial organic carbon. In addition, the better identification of source regions and spatial variability of climatic and geomorphic controls on transport processes will allow for a more accurate interpretation of stable isotopic compositions of plant waxes in paleoclimate reconstructions.

Plant-wax lipid biomarkers and their stable isotopic composition (expressed as δD or δ^{13}C value) are established methods to reconstruct paleoclimatic changes from sedimentary archives (e.g. Freeman and Colarusso, 2001; Schefuß, 2003; Tierney et al., 2008). The well-known altitude effect in precipitation isotopes (Dansgaard, 1964; Gonfiantini et al., 2001) has been shown to be recorded in plant wax δD values of living plants (Bai et al., 2011) and in soils (Ernst et al., 2013; Jia et al., 2008). Hence, plant wax δD values have been used in applications tracing vascular plant OM within rivers draining catchments with strong topographic gradients (Galy et al., 2011; Ponton et al., 2014). The resilience of plant waxes makes them a persistent tracer for plant-derived material, whether sourced directly from living plants or after storage in leaf litter and soils. Our approach follows a specific molecule, the C_{29} *n*-alkane, a biomarker for vascular plants. We note that the sources, pathways and fates of other biochemicals with different rates of degradation and different affinities for attachment and packaging with sediments will likely differ (e.g. Hatten et al., 2012; Hedges et al., 2000, 1994). The compound specific approach carries the power and limitations of this specificity within the heterogeneous OM pool. Depending on lithology, sources of *n*-alkanes can include fossil (petrogenic) organic matter (Tao et al., 2015). Studies employing plant waxes in fluvial catchments have revealed novel insights into transport processes: Galy et al. (2011) for example used δD values of plant wax *n*-alkanoic acids extracted from riverine particulate organic matter within the Ganges–Brahmaputra watershed. At the mouth of the Ganges–Brahmaputra, they found the low-elevation plains overwhelmed the contributions from the Himalaya. With more detailed progressive downstream sampling within the Madre de Dios River system in the Peruvian Andes, Ponton et al. (2014) similarly reported plant-wax *n*-alkanoic acid δD values in riverine particulate organic matter and in soils. From the equivalent isotopic gradients in soils and rivers they inferred that this material is representative of its respective catchment, in that fully-forested region. Seasonal contrasts in δD values of riverine particulate organic matter also revealed that during the wet season erosion increased in the higher elevations, which is an equivalent to 1 km higher in the effective catchment sourcing.

While physical erosion has been suggested to be the main driver of particulate organic carbon transport in large river systems worldwide (Galy et al., 2015), no study has yet attempted to assess the relative importance of biomass, climate, and erosional processes within a heterogeneous catchment. In this study, we quantify catchment-wide plant wax contributions from tributaries to the trans-Himalayan Arun River (33,508 km^2), covering a steep altitudinal (Fig. 1A) and climatic (Fig. 1B) gradient (cf. Bookhagen and Burbank, 2006; Olen et al., 2015). Whereas the lower catchment is characterized by tropical to subtropical evergreen forests, the higher Himalaya and the Tibetan Plateau are dominated by sparse alpine vegetation consisting of grasses and shrubs (Fig. 1C, cf. supplement A1 for more details) (Carpenter and Zomer, 1996; Dobremez and Shakya, 1975). We take advantage of the systematic change of plant wax δD (Ernst et al., 2013; Jia et al., 2008; Kahmen et al., 2013a; Peterse et al., 2009; Sachse et al., 2006; Tipple and Pagani, 2013) along altitudinal and hydrological gradients, and make use of it to characterize plant wax δD values along the Arun valley. Together with these observations we employ remote sensing techniques to estimate sourcing of plant-wax *n*-alkane contributions from across the catchment and identify climatic, ecological, and geomorphic drivers responsible for plant wax export from the tributaries.

2. Geographic setting

The Arun River drains the southern Tibetan Plateau (TP) and flows through the eastern Nepalese Himalaya before its confluence with the Tamor and Sun Koshi Rivers in the Siwalik Hills to form the Sapta Kosi (Fig. 1A). The altitudinal range of the catchment extends from 8848 m asl at the summit of Mount Everest to 203 m asl at its outlet into the Sapta Kosi over a horizontal distance of less than 160 km. Downstream, the Sapta Kosi continues ultimately into the Bay of Bengal via the Ganges–Brahmaputra River system. All sampled tributaries drain geological units of either the Greater Himalayan Sequence (late Proterozoic to early Paleozoic paragneisses, calc-silicates and schist) or the Lesser Himalayan Sequence (middle Proterozoic orthogneisses, phyllite, augen-gneiss and quartzite) (Bordet, 1961; Jessup et al., 2008; Quade et al., 2003; Stocklin, 1980). Hence, a contribution of petrogenic plant wax *n*-alkanes is not likely. The TP portion of the Arun catchment is dominated by well-preserved Cambrian to Eocene carbonates and siliclastic sedimentary rocks of the Tethyan Tibetan Zone that potentially contribute petrogenic OM to the Arun, including alkanes such as nC_{29} that are not derived from plant waxes. The plant wax molecular compositions of our samples were used to test this possibility.

The climate of Eastern Nepal is dominated by the Indian Summer Monsoon (ISM) contributing ~70% of the annual rain during its peak season between June and September (Bookhagen and Burbank, 2010). The Siwaliks in the south and the main Himalaya range, including Mount Everest and Makalu, act as orographic barriers to the ISM (Figs. 1B, 2) (Bookhagen and Burbank, 2006). The Tibetan region of the Arun receives very small amounts of rainfall, but additional snow from winter-westerly disturbances originating from the Caspian, Black and Mediterranean Seas (Bookhagen and Burbank, 2010; Lang and Barros, 2004). As a consequence of the climatic and hydrologic conditions, the vegetation in the Arun valley ranges from near-tropical evergreen forests in the south to sparse alpine vegetation in the high altitude part of the valley (Carpenter and Zomer, 1996; Dobremez and Shakya, 1975).

3. Methods

3.1. Sampling

Samples were obtained during two sampling campaigns in September 2011 and October/November 2012, indicated by first two digits of sample ID. River water was sampled at 37 locations (8 mainstem and 29 tributaries; Table 1). Water samples were taken to accompany each of the flood deposit and CPOM samples (see below). They were stored in gas-tight 2 ml glass vials that were flushed before being filled.

Leaves of modern trees and shrubs were sampled at 17 locations along the Arun Valley, at elevations ranging from 87 to 4070 m asl. Sampling of the same C_3 plant species throughout